



AFRL-RH-WP-TR-2008-0072

**Flexible Display and Integrated Communication
Devices (FDICD) Technology, Volume II**

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**L-3 Communications Display Systems
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**June 2008
Final Report for 14 April 2004 to 20 June 2008**

**Approved for public release;
distribution is unlimited.**

**Air Force Research Laboratory
Human Effectiveness Directorate
Warfighter Interface Division
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AFRL-RH-WP-TR-2008-0072

THIS TECHNICAL REPORT HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION.

FOR THE DIRECTOR

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Washington Headquarters Service, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.

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1. REPORT DATE (DD-MM-YYYY) June 2008		2. REPORT TYPE Final		3. DATES COVERED (From - To) 14 April 2004 – 20 June 2008	
4. TITLE AND SUBTITLE Flexible Display and Integrated Communication Devices (FDICD) Technology, Volume II				5a. CONTRACT NUMBER FA8650-04-C-6436	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER 62202F	
6. AUTHOR(S) David Huffman, Keith Tognoni, Robert Anderson				5d. PROJECT NUMBER 7184	
				5e. TASK NUMBER 11	
				5f. WORK UNIT NUMBER 28	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) L-3 Communications Display Systems 1355 Bluegrass Lakes Parkway Alpharetta GA 30004				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Material Command Air Force Research Laboratory Human Effectiveness Directorate Warfighter Interface Division Battlespace Visualization Branch Wright-Patterson AFB OH 45433-7022				10. SPONSOR/MONITOR'S ACRONYM(S) AFRL/RHCV	
				11. SPONSORING/MONITORING AGENCY REPORT NUMBER AFRL-RH-WP-TR-2008-0072	
12. DISTRIBUTION AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES 88 ABW PA Cleared 11 July 2008, WPAFB-08-4004					
14. ABSTRACT This flexible display and integrated communication devices (FDICD) technology program sought to create a family of powerful visualization technologies that would reduce the weight, volume, and power while increasing usability by integrating many of the functions of present mission equipment into a small form factor. The goals included a network comprising a worn main computer, a hand-held or knee-worn large display system and a wrist-worn small display. The large display was to be eventually rollable to provide soldiers with a large image of at least super video graphics adapter (SVGA) color resolution when needed, but small form factor when stowed, for viewing of and team collaboration with tactical information such as battlefield maps, GIS imaging data, command/control plots, and global positioning system (GPS)-assisted navigational maps. The wrist system was to provide a readily viewable unit in situations where the larger unit cannot be deployed and without resorting to headgear, which blocks battlespace view-ability. This final phase of the program resulted in two separate wrist demonstration devices. The first device built upon the results of the first phase of the project to raise the technology readiness level (TRL) of the commercial personal digital assistant (PDA)-based unit to a level suitable for the intended military environment, including full water-immersion capability. The second device was a custom designed wrist display intended to demonstrate additional capability on the wrist, including GPS maps.					
15. SUBJECT TERMS integrated communication device, Wrist Attached Video Equipment, WAVE, wrist computer, wearable display, streaming video, rollable screen, flexible display, battlefield air operations, BAO kit					
16. SECURITY CLASSIFICATION OF: Unclassified			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 56	19a. NAME OF RESPONSIBLE PERSON Dr. Darrel G. Hopper
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			19b. TELEPHONE NUMBER (Include area code)

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FOREWORD

This contract FA8650-04-C-6436 was awarded 14 April 2004 to L-3 Communications Display Systems (L-3 DS), <http://www.L-3com.com/displays> under Air Force Research Laboratory (AFRL) Program Research & Development Announcement (PRDA) No. 04-02-HE, entitled "Flexible Displays and Integrated Communications Device (FDICD) Technology," published 5 Dec 03 in FedBizOps as a result of an FY2004 \$1.5M Congressional mark entitled "Flexible Display and Integrated Communication Device for the BAO." Congressional authorization language in the House Armed Services Committee Report HASC Report 108-106, pages 200 and 217 was as follows:

"Integration of ground targeting cueing through data link to combat aircraft to reduce the "target-to-shooter" time-line is critical to improving close air support, target identification, and designation and to reduce "blue-on-blue" casualties. Flexible displays and integrated communications devices are key to realizing this capability. The committee authorizes an increase of \$2.0 million in PE 62202F for integration of leading-edge global positioning, communications components, voice messaging, displays, and related technologies to provide flexible display and integrated communications devices."

Prior work by L3DS funded under a separate AFRL support contract had resulted in a breadboard wrist-mounted display monitor based on commercial active matrix liquid crystal display (AMLCD), which L3DS called Wrist Attached Video Equipment (WAVE). Demonstration of this breadboard, now referred to as WAVE Spiral 1, lead to user requests to develop prototypes with a range of additional functionalities, beyond simple display. This prior L3DS WAVE 1 effort was initiated by AFRL to gain industry participation in developing a 2002 AFRL initiative to develop "on-the-move" wearable displays.¹

Phase 1 of the presently reported FDICD contract took place from 14 April 2004 – 13 June 2006. This earlier work has been documented in technical report:

David Huffman, Keith Tognoni, Robert Anderson, Michael Hack, Anna Chwang, Richard Hewitt, Robert A. Street, Jackson Ho, JengPing Lu, and Darrel G. Hopper, "Flexible Display and Integrated Communication Devices (FDICD) Technology," AFRL-HE-WP-TR-2006-0125, 172 pp (September 2006)

which is available to Government Agencies only via the Defense Technical Information Center (DTIC). The Phase 1 effort focused primarily on flexible display research with most of the work performed under subcontract to Universal Display Corporation (UDC) and its key vendor, Xerox Palo Alto Research Center (PARC). However, Phase 1 also included a task under which L3DS advanced its concept of a smart wrist display system with its development of WAVE Spirals 2.0 and 2.5. Spiral 2.0 was a complete systems integration design concept with all hardware and software components selected by L3DS. Spiral 2.5 was a packaged personal digital assistant (PDA) approach in which the PDA selected for ruggedization was one used by L-3

¹ Fred M. Meyer, Sam J. Longo, and Darrel G. Hopper, "Wrist display concept demonstration based on 2-in. color AMOLED," in *Defense, Security, and Cockpit Displays*, Proceedings of SPIE Volume 5443, pp. 257-268 (2004).

Communications Systems – West as optional equipment for its uninhabited air vehicle (UAV) common ground terminal system called Rover. The work on WAVE Spirals 2.5 and 2.0, respectively, led to the presently reported Phase 2 work on WAVE Spirals 3 and 4.

An FY2006 \$1.0M Congressional mark entitled FDICD enabled the presently reported Phase 2 of the FDICD contract, which took place from 20 June 2006 – 20 June 2008. This Phase 2 research focused entirely on wrist systems under an amendment to the original contract, which was funded with \$873,000 government funding and \$53,460 of L-3 DS cost share with hardware deliverables due 20 February 2008 and the final report, by 20 June 2008. A key subcontractor for Spiral 3 was Slingshot Product Development Group in Lawrenceville GA, <http://www.slingshotpdg.com/index.html>. Key subcontractor/vendors for Spiral 4 were Anders Electronics in London, United Kingdom and their subsidiary location in Haifa, Israel. This report documents the results of the FDICD Phase 2 effort.

This report has been formatted in accordance with a commercial standard, with tailoring from the AFRL Scientific Technical Information Office. This standard is as follows: “Scientific and Technical Reports—Elements, Organization, and Design,” American National Standard ANSI/NISO Z39.18-1995 (NISO Press, Bethesda MD, 1995), which is available electronically via the following website address: <http://www.wrs.afrl.af.mil/library/sti-pubh.htm>

The government technical review of this document was accomplished by Dr. Darrel G. Hopper of AFRL.

PREFACE

The long-term objectives of this effort are summarized in the Congressional language quoted above. Phase 2 of the AFRL contractual effort continued the work begun in fiscal year 2004 with concentration on the integrated communications aspects of FDICD devices.

The wireless wrist display tasks required L-3 DS to develop and deliver a wrist-worn display capable of wireless interface to a PC-compatible wearable computer or similar processor. The wrist display was to incorporate a thin-film transistor (TFT) AMLCD suitable for daytime or nighttime viewing, wireless connectivity using commercially accepted standard interfaces, embedded microcontroller, and operator controls to allow cursor control for global positioning system (GPS) applications and other user interactions. The wrist display was required to be a prototype suitable for user evaluations of ergonomics, display quality / formats, and wireless functionality. The display size was required to be nominally 2.5 inches diagonal. The unit was required to be demonstrated with moving video and with interface to a ruggedized PC-compatible computer. A separate battery unit was required to be supplied if an internal battery was not feasible for the prototype.

Task 3 of the modified contract was to refine the WAVE 2.5 breadboard developed during Phase 1 into a prototype for field evaluation in a relevant environment. This new, more rugged, device was called WAVE Spiral 3, as it represented the third evolution of the concept of wearable display and processing done under the FDICD project. This Spiral 3 device was based on a Hewlett Packard iPAQ Pocket PC personal digital assistant (PDA) and was designed into a housing capable of full military environmental performance and full water-immersion to one meter. The effort performed on this task raised the technology readiness level (TRL) of the device to TRL 6 (suitable for operation in a relevant environment).

Task 4 of the modified contract was to design a custom form-factor wearable display device using an AMLCD and Windows operating system capable of containing increased memory and with embedded GPS capability. This device was labeled as WAVE Spiral 4 in the contract and in this report. It represented a TRL 4 level device (suitable for evaluation in a laboratory environment). The Spiral 4 device was intended to act as a testbed for new wearable hardware and software applications.

The modified contract also included the requirement to update the technology roadmap for FDICD, which was initiated during Phase 1 of the contract.

Hardware deliverables to Air Force under Phase 2 of the contract were as follows:

Qty 10: Spiral 3 wearable display devices;

Qty 10: Spiral 4 wearable display devices.

ACKNOWLEDGEMENTS

We gratefully acknowledge the financial support received from the Air Force and thank Dr. Darrel G. Hopper of the Air Force Research Laboratory (AFRL) for his keen technical insights and guidance of this effort on behalf of the government. We commend government personnel from AFRL (Dr. Hopper), the U.S. Army Research, Development and Engineering Command (RDECOM) Communication and Electronics Research and Development Engineering Center (CERDEC) (Mr. Raymond Schulze), and the RDECOM Army Research Laboratory (ARL) (Drs. Eric W. Forsythe and David C. Morton) for their remarkable cooperation, which enabled us to achieve synergy amongst several separate contracts for the flexible display and integrated communications device tasks.

1. SUMMARY

This second phase of the contract continued the work initiated under Air Force contract to perform research and development into flexible displays and integrated communication devices (FDICD) technology. The first phase focused primarily on flexible display technology and was conducted by L-3 Communications Display Systems, Universal Display Corporation, and Palo Alto Research Corporation. This second phase focused on the refinement and development of wearable communication technology.

Two versions of wearable communication devices were produced during Phase 2 of the FDICD contract. Because the primary application for the communications on the device is to provide video to the warfighter from a variety of sources, both devices were referred to by L-3's internal name for the technology, Wrist Attached Video Equipment (WAVE). The first version of WAVE developed under FDICD Phase 2 was designated as "Spiral 3," which represented a design using a commercially available personal digital assistant (PDA) from Hewlett Packard as the base for the device. This technology had to be hardened and reconfigured, both in hardware and software, for the needs of the Air Force users (TRL 6). Ten Spiral 3 units were delivered under the contract.

The second device delivered and described in this report was designated as "Spiral 4" and was intended as a test bed for obtaining further user evaluations of wearable computing applications and ergonomic considerations in the design of wearable electronics (TRL 4). This unit was custom designed for the program and ten units were delivered for evaluation.

In addition to hardware development, a technology roadmap was updated for the FDICD wearable electronic devices family. The purpose of the roadmap is to identify key technology areas of interest which would be beneficial for future integration into an FDICD-type device for the warfighter. This roadmap was intended to be used to help determine desired features and priorities for future research in the wearable display devices field.

The data and research gained from this effort will be used in conjunction with the ongoing flexible display technology being jointly developed by the Air Force and Army as that technology gains sufficient maturity for survival in the typical military environment.

2. INTRODUCTION

The Air Force and Army are developing flexible display and integrated communication device technology with the vision of combining leading edge communications technology with a high performance rollup display. Key attributes of the flexible displays researched during Phase 1 (2004-2006) of this contract include high information content, low power consumption, video rate performance, and fabrication on a flexible substrate. The flexible display research task accomplished under Phase 1 of this contract has been documented in a previous report submitted to the Defense Technical Information Center:

David Huffman, Keith Tognoni, Robert Anderson, Michael Hack, Anna Chwang, Richard Hewitt, Robert A. Street, Jackson Ho, JengPing Lu, and Darrel G. Hopper, "Flexible Display and Integrated Communication Devices (FDICD) Technology," AFRL-HE-WP-TR-2006-0125, 172 pp (September 2006).

The flexible display research has been continued under separate Army and Air Force contracts. The effort covered by this report continued the communication electronics portion of the FDICD development initiated during Phase 1 so that advances in processing and miniaturized electronics functions could be explored while the flexible display technology matured.

For this Phase 2 of the FDICD contract, two separate devices were to be designed, manufactured, tested, and delivered to AFRL. The first device was to be a ruggedized PDA packaged so that it could withstand the rigors and shocks of the typical military environment including immersion in one meter of water. This type of device represented the use of commercial computing technology adapted for the military. This ruggedization approach allowed the military to take advantage of some of the cost savings associated with commercial equipment and to gain benefit from technology advances occurring at a rapid pace in the commercial hand-held device market. The technology roadmap task was continued during this Phase 2 and included a roadmap for flexible display technology in addition to the integrated communications functions necessary for FDICD. Demonstrations, breadboards, and prototypes delivered under this phase and other related contracts were analyzed to develop the roadmap.

2.1 Technical Requirements and Approach – Spiral 3

The requirements for the Spiral 3 WAVE device were as stated in Phase 2 task A.2.2.4 of the modified contract statement of work:

A.2.2.4 Wrist Attached Video Equipment (WAVE) Spiral 3.0:

The brassboard wrist display delivered under Task A.2.2.3 (WAVE Spiral {2.5}) will be enhanced and modified to bring it to a sufficient level of ruggedness so that field evaluations can occur. The Spiral {2.5} device delivered in March 2006 had a Technology Readiness Level (TRL) of TRL 4, which allows for operation under laboratory conditions; the enclosure package was a stereolithographic assembly (SLA) which consists of finely layered plastic. In this task the Contractor shall raise the TRL level of the wrist device to at least TRL 6 for evaluation under real world conditions by Air Force personnel in real or simulated military environments. In order to accomplish this, the following modifications shall be accomplished: SLA enclosure will be redesigned and replaced with an injection-molded housing for more ruggedness; seals will be incorporated so that the unit can withstand immersion in water; the operator's pushbutton functions will be implemented to allow use; environmental confidence testing, such as

vibration, temperature, shock, and drop test will be performed and documented; testing to the requirements in accordance with MIL-STD-810E; functioning Battery Module for extended missions; optimized Wrist Band with protective fabric covering; tethered stylus; Bluetooth, WiFi 802.11b&g; Windows Mobile 5.0; and touchscreen. Ten (10) units of this spiral (Spiral 3.0) will be delivered to the Air Force six months after award (6 MARO).

L-3 Communications Display Systems (L-3 DS) contracted with Slingshot Product Design Group (SPDG) in Lawrenceville, GA to mature the ruggedized PDA design (WAVE Spiral 2.5) developed by L-3 DS under Task A.2.2.3 BASE EFFORT WIRELESS WRIST DISPLAY TASK during Phase 1 of this FDICD contractual effort. Slingshot was to perform the necessary packaging redesign to ensure that the resulting ruggedized PDA device (WAVE Spiral 3.0) could operate in a relevant military environment (TRL 6). Slingshot used focus groups and product surveys to determine the best overall form factor for the new design and implemented several prototype devices in plastic. These early units were used in preliminary mechanical tests and in subjective ergonomic evaluations with L-3 users. The most significant design constraint was the requirement to operate after immersion in one meter of water for thirty minutes. This requirement meant that each opening in the outer shell of the casing had to be protected at all times from leakage, yet still function in its intended role. Ports, such as the Universal Serial Bus (USB) and serial data input output (SDIO) ports, had to be accessible to the user, but sealed and impervious to water penetration when not in use. These ports were not usable while the unit was immersed due to the sealing plug used in the design. WAVE Spiral 3 is illustrated in Figure 1a.

2.2 Technical Requirements and Approach – Spiral 4

At the same time that the L-3 team was working on the Spiral 3 WAVE device, a separate group was working in parallel on the next generation of wearable device, named the Spiral 4 WAVE. The objective of the Spiral 4 effort was to package a Microsoft Windows-compatible processor along with increased memory and embedded GPS into as tight a form-factor as possible. The requirements for the Spiral 4 WAVE device were as stated in Phase 2 task A.2.2.5 of the modified FDICD contract statement of work:

A.2.2.5 Wrist Attached Video Equipment (WAVE) Spiral 4.0:

The Contractor shall develop and deliver a Spiral 4.0 wearable display with increased integrated communication capability. This spiral will build upon the functions present in the Spiral 3.0 device from Task A.2.2.4. The Contractor shall incorporate the following new functions to be into this Spiral 4.0 device: integrated (embedded) GPS and or other navigational capability; night vision compatible filter for NVIS Class A; and increased memory capacity to at least 1 GByte. The Contractor shall investigate and may incorporate additional features in the Spiral 4.0 device as follows: digital camera; biometric sensor for security identification; alternate methods of power generation (e.g. solar cells, mechanical); and high-speed low-power processor (such as the HyperX). Ten (10) units of this spiral (Spiral 4.0) will be delivered to the Air Force twelve months after award. (12 MARO).

For the Spiral 4 approach, L-3 performed the majority of the mechanical packaging work and subcontracted the electrical development and software generation to Anders Electronics (UK). Anders was chosen due to the availability of their CM-X270L processor board. This board offered a wide variety of interfaces in addition to a powerful processor capable of running Windows or Linux applications. The chosen technical approach for Spiral 4 was to build upon the existing central processing unit (CPU) board (CM-X270L) and have Anders design a base

board which would complement the CPU board and provide room for Air Force specific requirements, such as GPS and 1 GB of memory. This base board hardware design was subcontracted by Anders to Valigent, Ltd. of Haifa, Israel. A separate battery module was to be designed by L-3 to accommodate external batteries and to provide space for interface connectors.

The Spiral 4 WAVE device was intended to function as a technology demonstration platform for user evaluation in a more benign environment. Primary goals were to reduce the weight and form factor, provide an embedded global positioning system (GPS) capability, provide 1 GB of internal memory, and incorporate as many additional communications functions as possible within the space and power constraints of the device. The WAVE Spiral 4 was focused on a highly modular approach to allow implementation of a technology demonstration platform that can easily adapt new and enhanced capabilities. The goal was to enable the program to take advantage of advances in FDICD-related technologies as they become practical to implement or demonstrate. A key objective was to enable a swift and straightforward path to deployment and to demonstrate the capacity to leverage off best in class technologies without extensive redesign. Spiral 4 was also to provide the potential to be customized and repackaged into mission specific configurations. WAVE Spiral 4 is illustrated in Figure 1b.

2.3 Technical Requirements and Approach – Roadmap

The requirements for the FDICD roadmap were stated in continuing task A.2.2.2 as follows:

Sow Task A.2.2.2: Continue to refine the functional roadmap for the FDICD and cooperate with an in-house Air Force effort to develop the roadmap covering a ten-year spiral development period and to verify the completeness of the roadmap through interaction with the user community. Assist in the conduct of user evaluations and field trials when requested by Air Force Research Laboratory.”

During Phase 2 of the contract, the roadmaps were updated to reflect the actual maturity level of the flexible display device technology and specific implementations for certain functions were investigated. L-3 DS continued to track developments in the field of wearable and portable electronics and revise the technology roadmap and funding roadmap. The purpose of the roadmap task was to maintain a plan-ahead path which could be used to guide future spiral requirements for wearable communication devices utilizing the flexible display technology when it is developed. The desired functions of the WAVE devices included wireless communications, common user electrical interfaces, video and imagery functions, secure communications, and user input device technologies. Many of these desired functions were determined by feedback given by the Air Force user community, particularly the 720th Special Tactics Group at Hurlburt Field FL and other knowledgeable users. Developments in consumer portable communications technologies over the coming years are expected to lend themselves to integration into packaging for the military environment. Adequate security and environmental adaptations will still be necessary to incorporate for the Air Force and Army user to enable effective use of these commercial-based technologies. Other government-funded research into power sources outside the scope of this contract will also have a direct beneficial impact on the mission of the FDICD device, as the addition of communications functions and higher speed wireless communication dictate the need for more efficient energy storage and utilization. Updated functional and programmatic versions of the FDICD roadmap are presented in Section 3.3.



Figure 1a: WAVE Spiral 3.



Figure 1b: WAVE Spiral 4.

3. METHODOLOGY AND RESULTS

The wireless wrist display tasks required L-3 DS to develop and deliver wrist-wearable visualization systems capable of wireless interface to a PC-compatible wearable computer or similar processor that incorporated a commercially available nominally 2.5-in. diagonal thin-film transistor active matrix liquid crystal display (TFT AMLCD, aka LCD) suitable for daytime or nighttime viewing, wireless connectivity using commercially accepted standard interfaces, embedded microcontroller, and operator interface to allow cursor control for GPS applications and other user interactions. The wrist display was required to be a prototype suitable for user evaluations of ergonomics, display quality / formats, and wireless functionality. The unit was to be demonstrated with moving video and interface to a ruggedized PC-compatible computer. A separate battery unit was required if an internal battery was not feasible. The tasks included investigations of battery and touchscreen technologies.

3.1 Spiral 3 Wearable Display Device

3.1.1 Background for Spiral 3

A wrist-mounted display capable of GPS reception, streaming video feed (both wired or wireless), rechargeable and/or quick change battery, transfective LCD, and USB throughput were basic requirements for the WAVE. A low-power, yet high-resolution LCD of nominal 2.5 to 3.0 inch diagonal viewing area was desirable. The unit had to be worthy of surviving a wrist mounted environment in hostile conditions, including three foot immersion in water.

The Spiral 3 WAVE packaging design was subcontracted by L-3 DS to Slingshot Product Design Group (Duluth, GA). Slingshot specializes in the mechanical packaging of commercial products and design for producibility. A specification was developed based upon the Air Force requirements and regular design reviews were held to ensure that the final package would be able to meet the necessary environmental and ergonomic requirements for a wearable display device.

3.1.2 Mechanical Design for Spiral 3

An exploded schematic view of the Spiral 3 device internal design is illustrated in Figure 2. Two rugged housing halves enclose the essential electronics (of an HP iPAQ hx2490 Pocket PC) and a submersion proof switch array is located to the inside of the wearer's wrist. The design functions either right or left handed. Internal to the unit is a socket that can accept a variety of commercially standard SDIO devices. This sealed package also contains the two internal batteries that came with the iPAQ (rechargeable Li-ion, button) and the iPAQ input/output/power interface port. A third, removable auxiliary battery pack consisting of a housing, printed wiring board (PWB), interface connector, and two AA batteries, is available; this auxiliary pack can be clipped on or removed with a gloved hand. A wrist strap that could accommodate various wrist sizes and wear options (such as outside thick clothing) was also conceived and prototyped. The external battery clip was designed to hold two common AA batteries. The AA batteries in the detachable auxiliary battery clip can supply power to the iPAQ's internal rechargeable lithium ion battery. The auxiliary battery clip could be removed from the unit while the unit was in operation, so that continuous battery operation could result as new AA batteries were installed to prevent depletion of the iPAQ's internal battery.

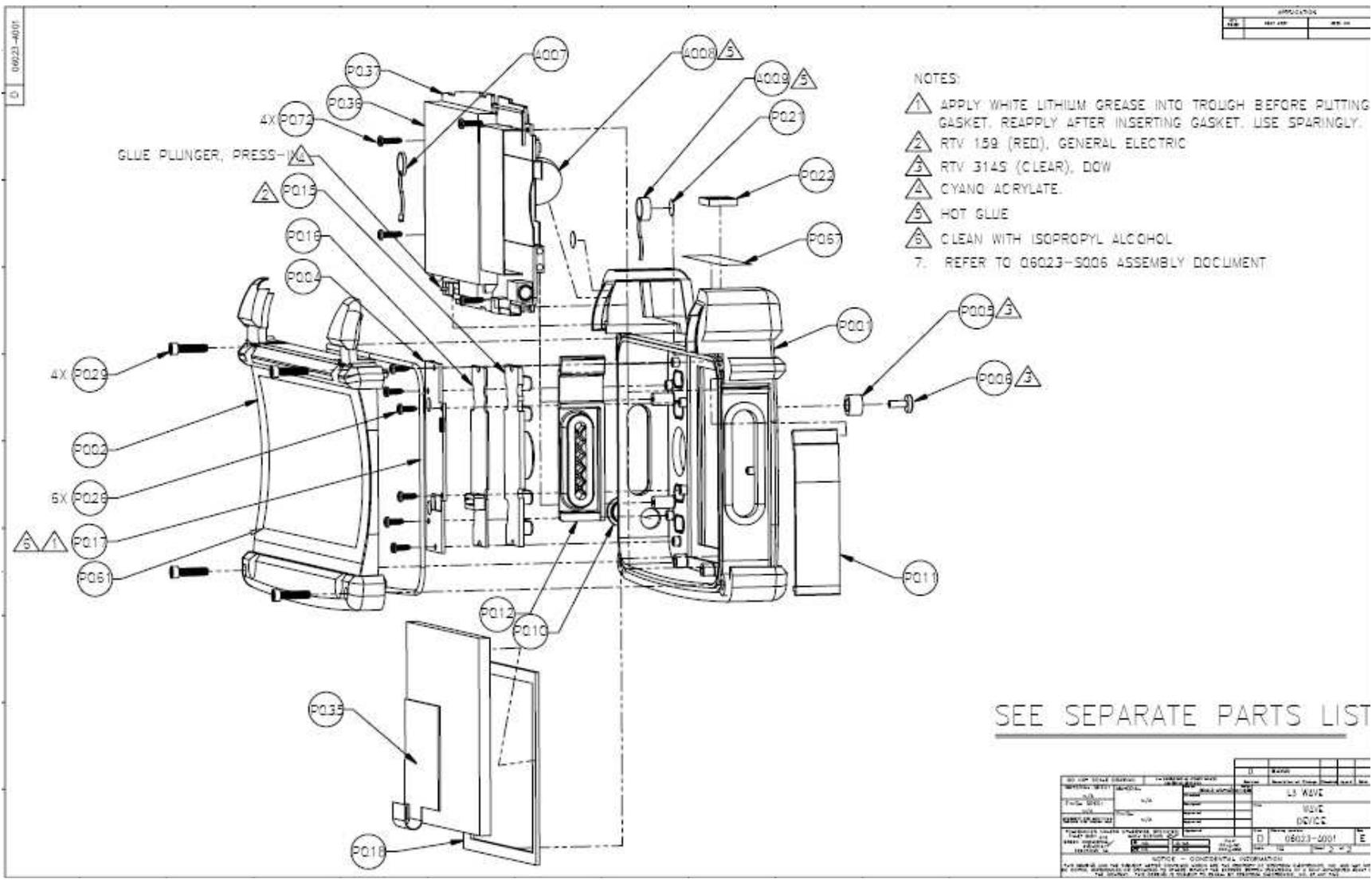


Figure 2: Mechanical top level exploded view of Spiral 3 WAVE device.

The electrical elements internal to the WAVE 3 device are illustrated in Figure 3. Custom printed circuit boards were required so that the normal operation of the HP iPAQ's front panel pushbuttons could be maintained even though the location of the buttons relative to the processing circuit had to be changed for packaging reasons.

Figure 4a is a drawing of the top level elements of the Spiral 3 WAVE with an early, conceptual wrist strap. A photograph of a WAVE 3 unit is illustrated in Figure 4b with a wide Velcro cinch-strap designed for easy one-handed donning and doffing. Velcro is on the wrist side of WAVE 3.

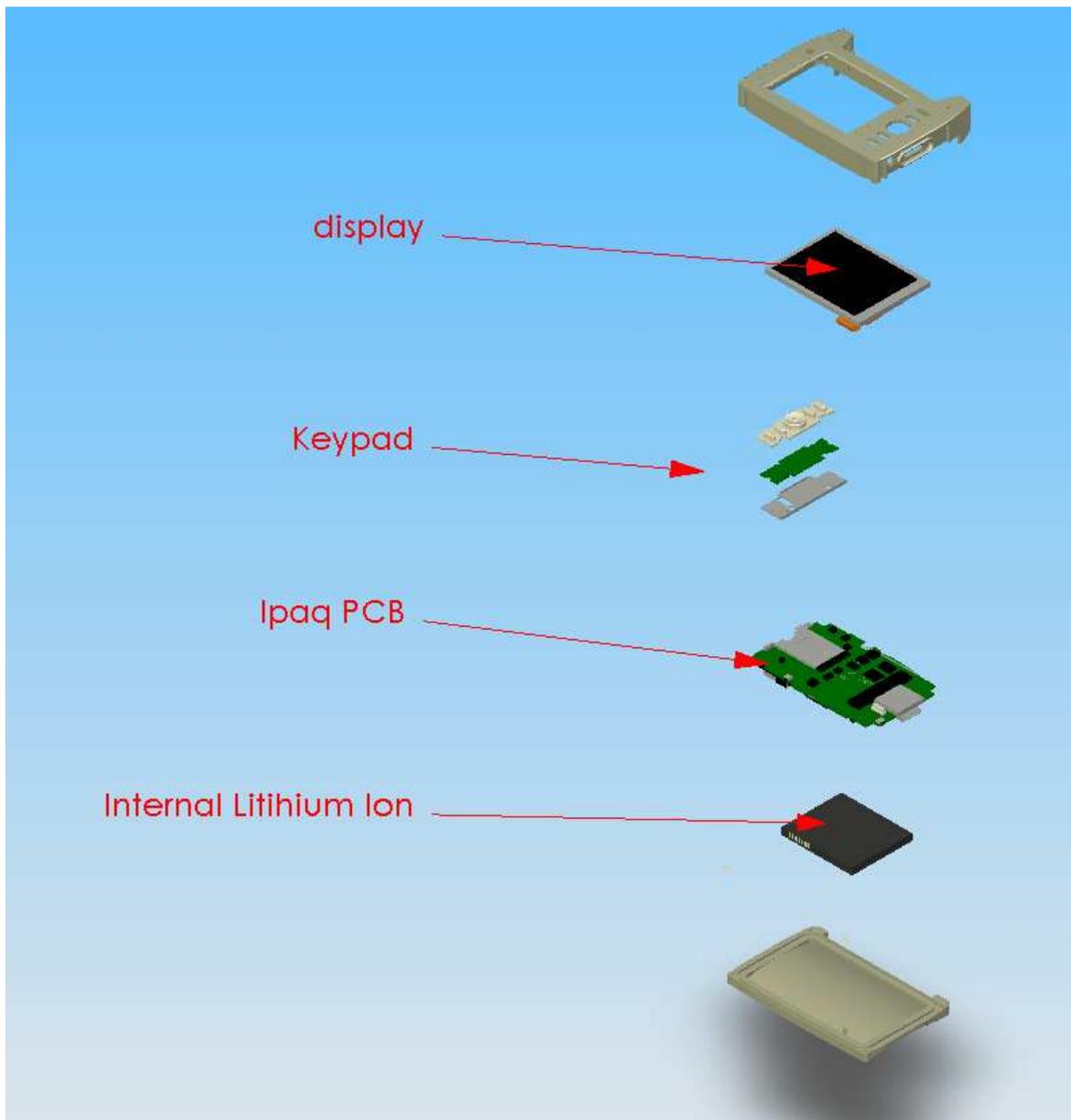


Figure 3: Internal circuit boards in exploded Spiral 3 diagram.

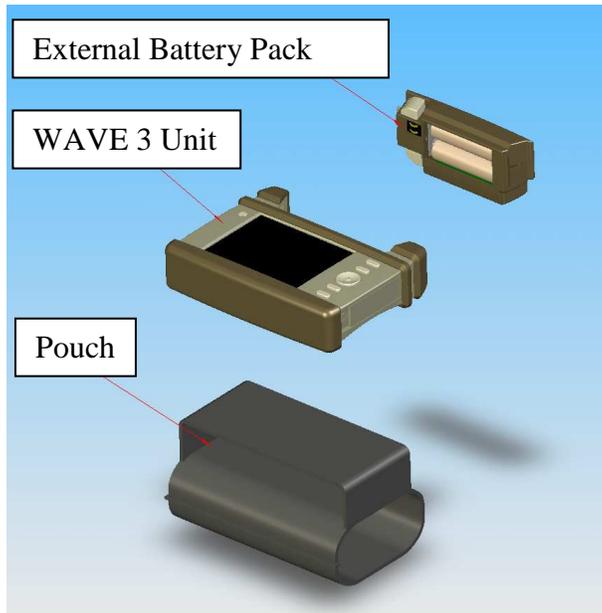


Figure 4a: Top level Spiral 3 unit with battery module and early concept wrist pouch.



Figure 4b: Photo of WAVE 3 system with wide velcro cinch strap for one-handed don/doff.

3.1.3 Sealing Design for Spiral 3

The most difficult aspect of the design of the Spiral 3 WAVE was the requirement to meet the immersion in one meter of water and to continue operation upon completion of the test. Each port in the external packaging had to have a separate sealing design worked out so that the port or pushbutton for the iPAQ could continue its normal function, but was sufficiently sealed to prevent encroachment of water into the interior of the unit upon immersion, which would result in device failure.

The following charts show each of the “breaches” in the outer device shell and the specific details incorporated into the final design to overcome the sealing problem. Figure 5 shows the various ports, each of which must be protected to prevent leakage. Figures 6 through Figure 18 illustrate in detail the design considerations required and specific design features incorporated to allow the sealing requirement to be met for individual ports.

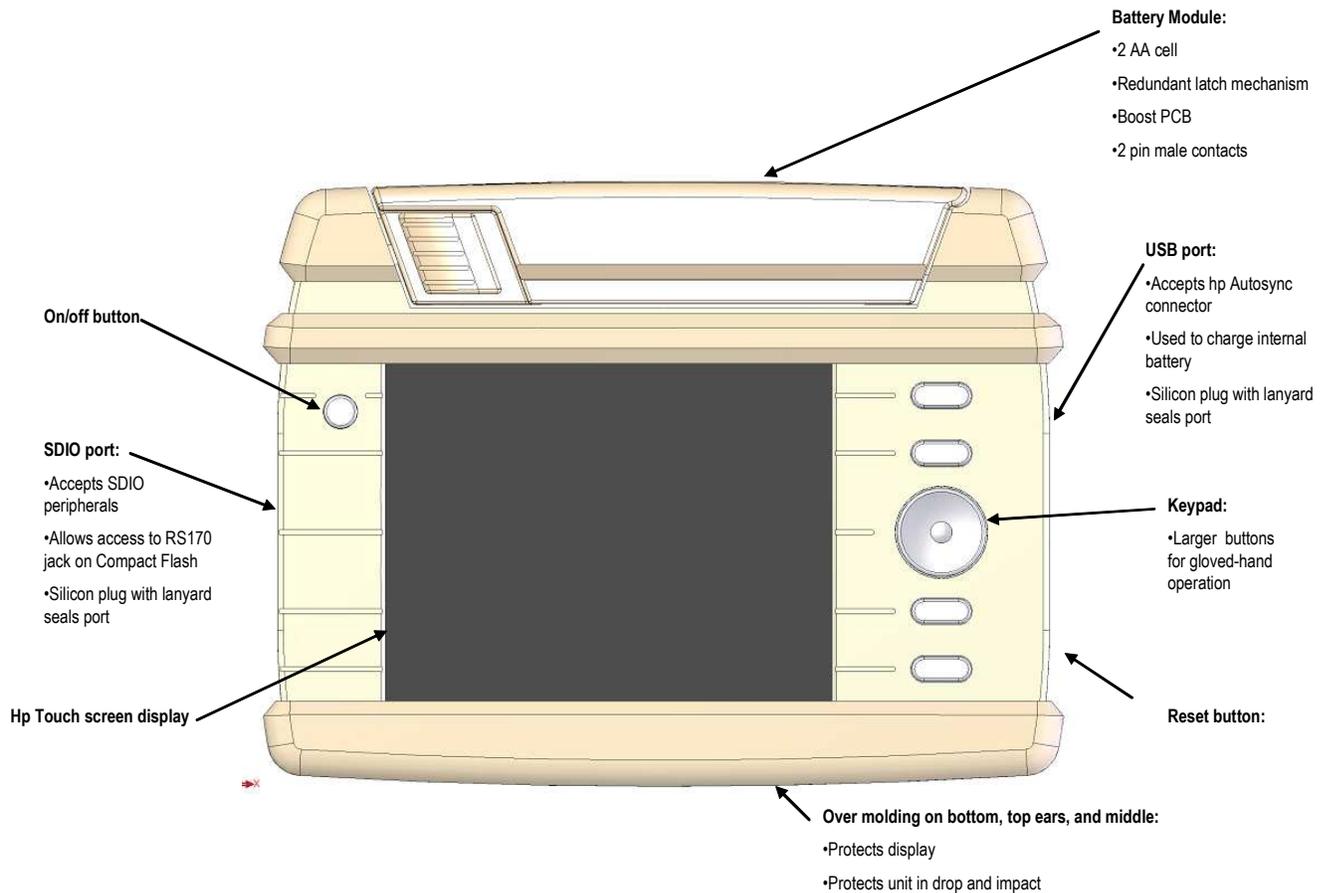
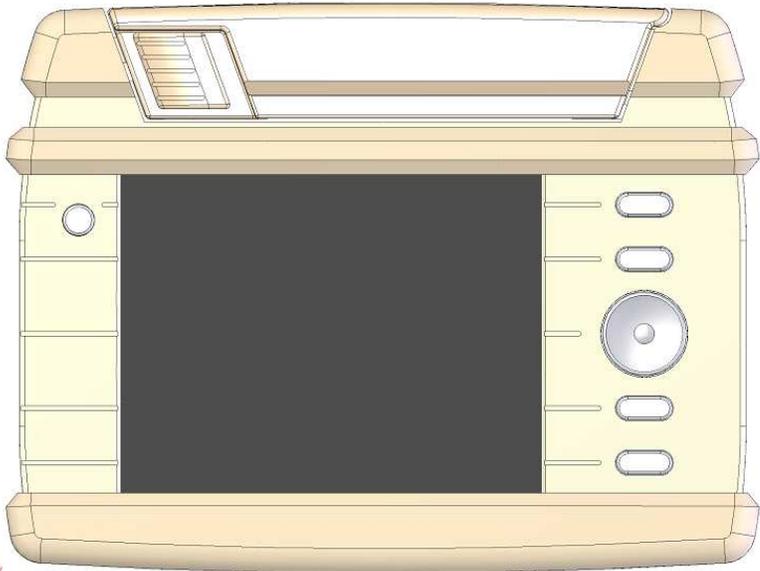


Figure 5: WAVE Spiral 3 ports and features requiring sealing provisions to prevent leakage.

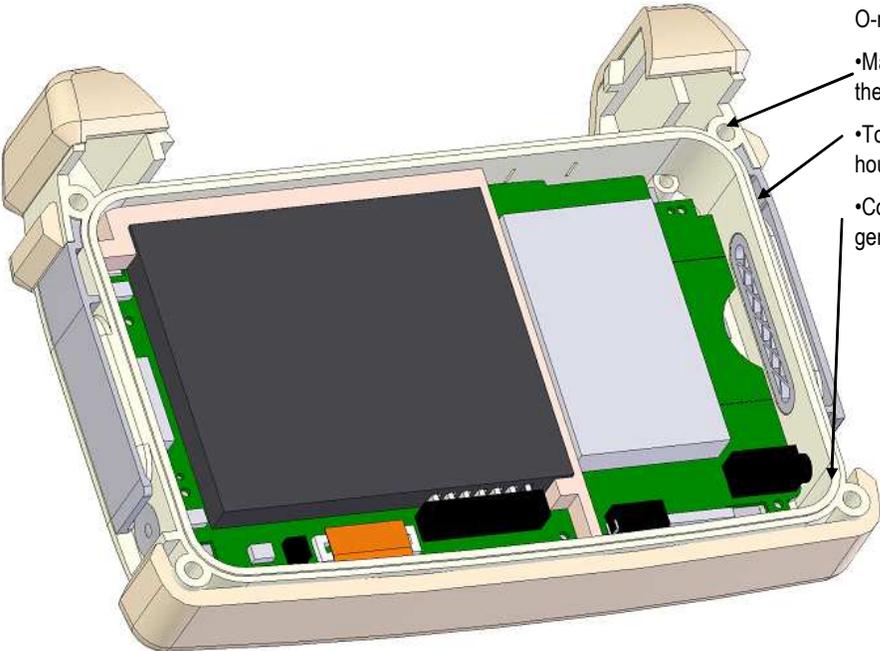
Sealing Challenges



- Sealing challenges:**
- Housing parting plane
 - USB plug sealing
 - SDIO plug sealing
 - Display sealing
 - On/off button sealing
 - Reset button sealing
 - Keypad sealing
 - Battery contact sealing

Figure 6: Primary sealing challenges for Spiral 3.

Parting Plane Sealing



- Tongue and groove features compress a hollow core Parker O-ring
- Main case fasteners are outside the seal path
- Tongue features are in the front housing
- Corners of sealing path have gentle radius

Figure 7: Parting sealing design for Spiral 3.

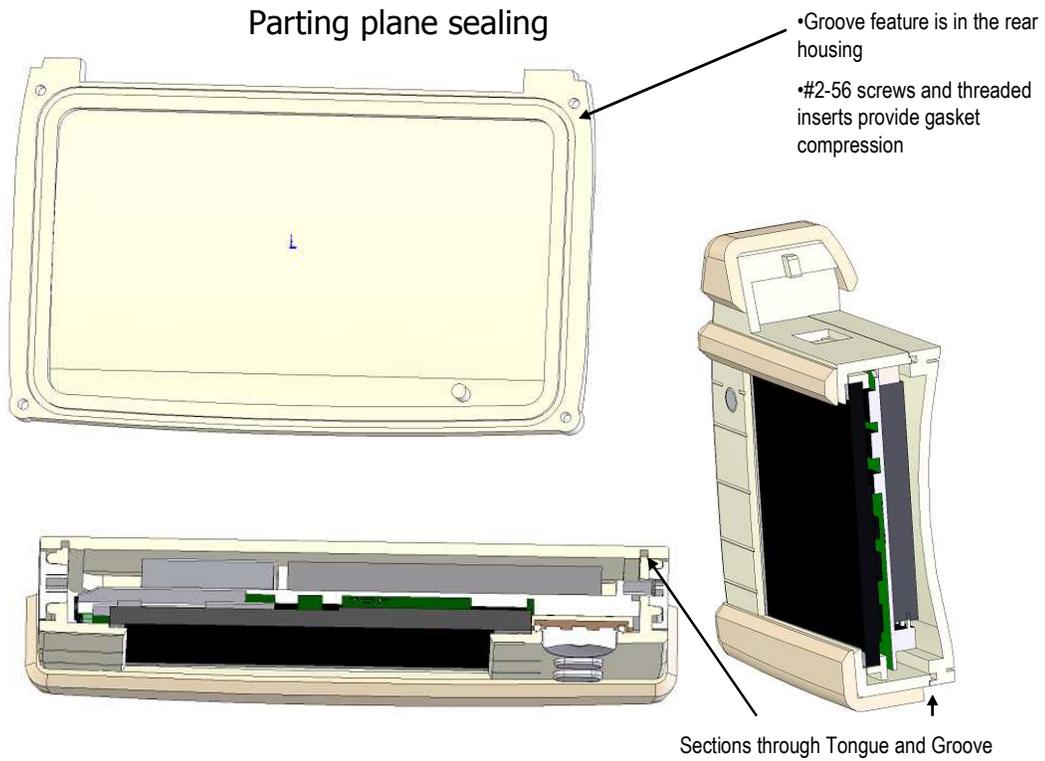


Figure 8: Design provisions in packaging for parting plane sealing of Spiral 3.

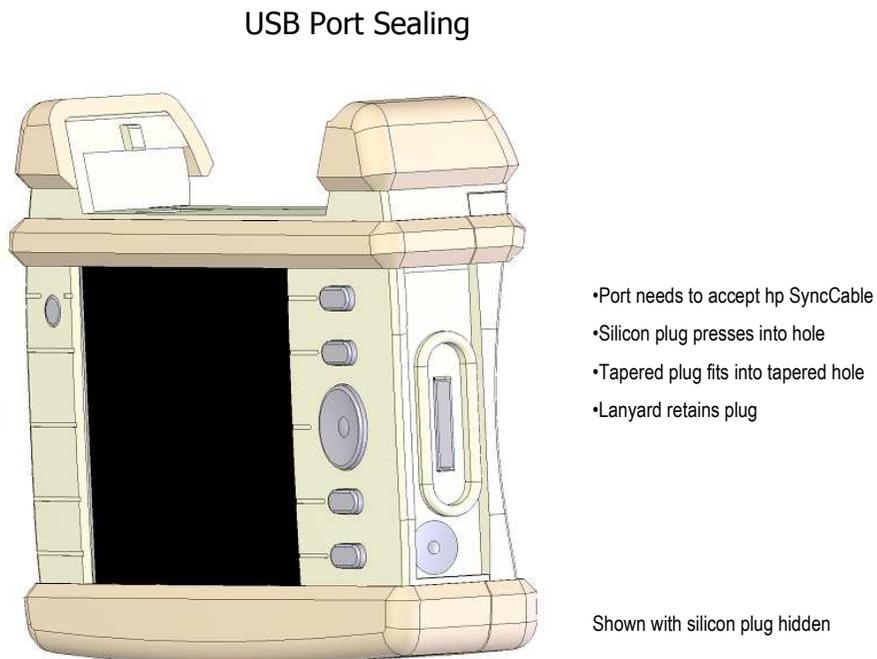


Figure 9: Design considerations for USB port sealing of Spiral 3.

USB Port Sealing

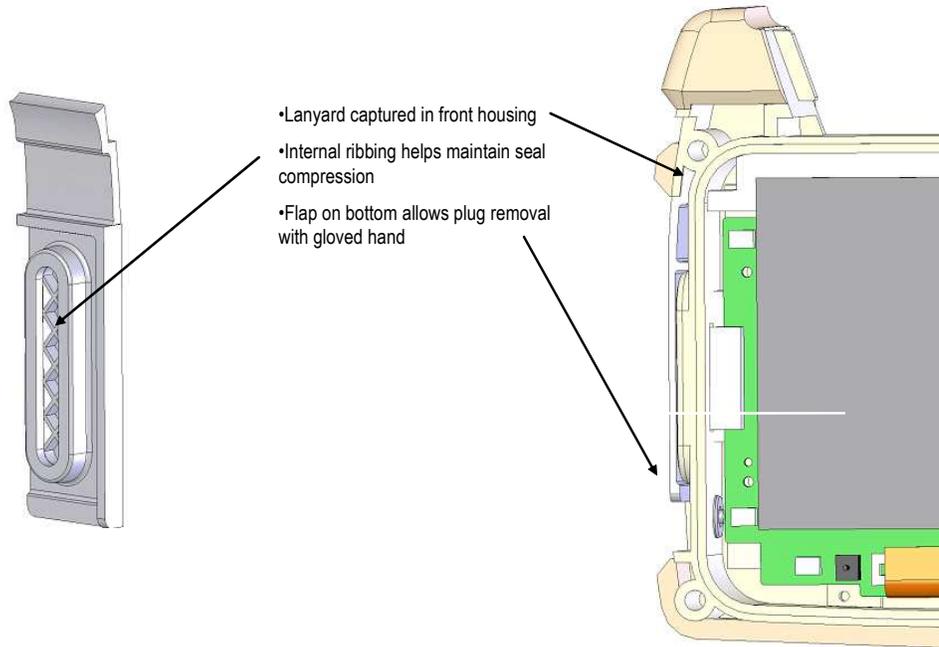
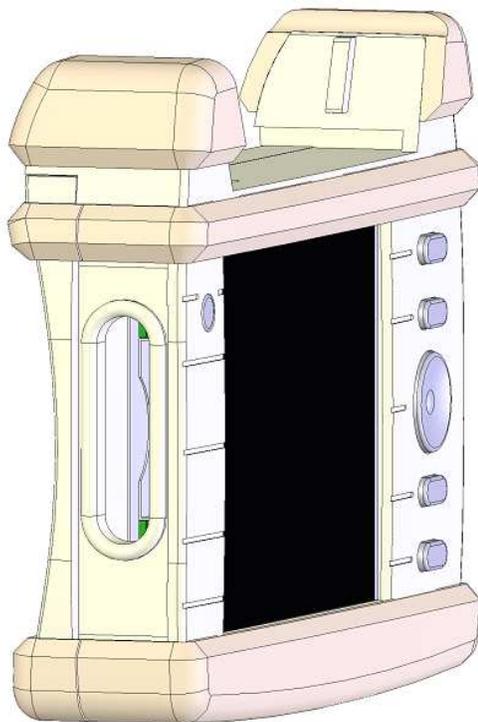


Figure 10: Design features for USB port sealing of Spiral 3.



SDIO Port Sealing

- Must allow SDIO access for peripherals
- Allow access for RS170 jack on back of CF slot
- Silicon plug presses into hole
- Tapered plug fits into tapered hole
- Lanyard retains plug

Shown with silicon plug hidden

Figure 11: Design considerations for SDIO port sealing of Spiral 3.

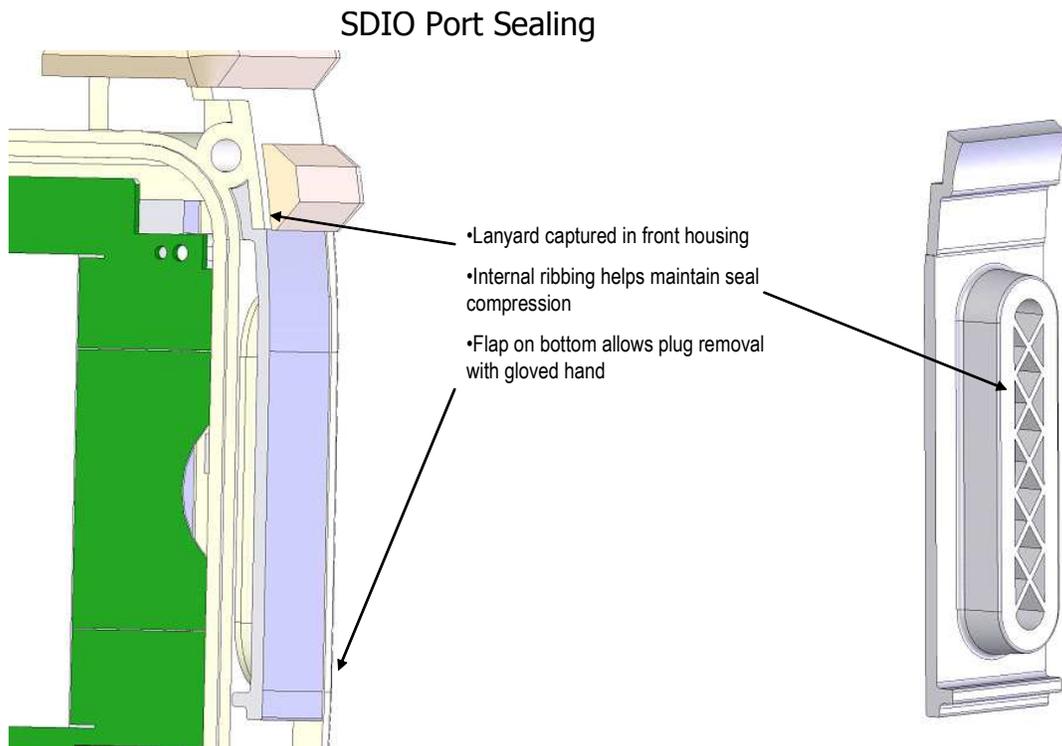


Figure 12: SDIO design features to accommodate sealing requirement for Spiral 3.

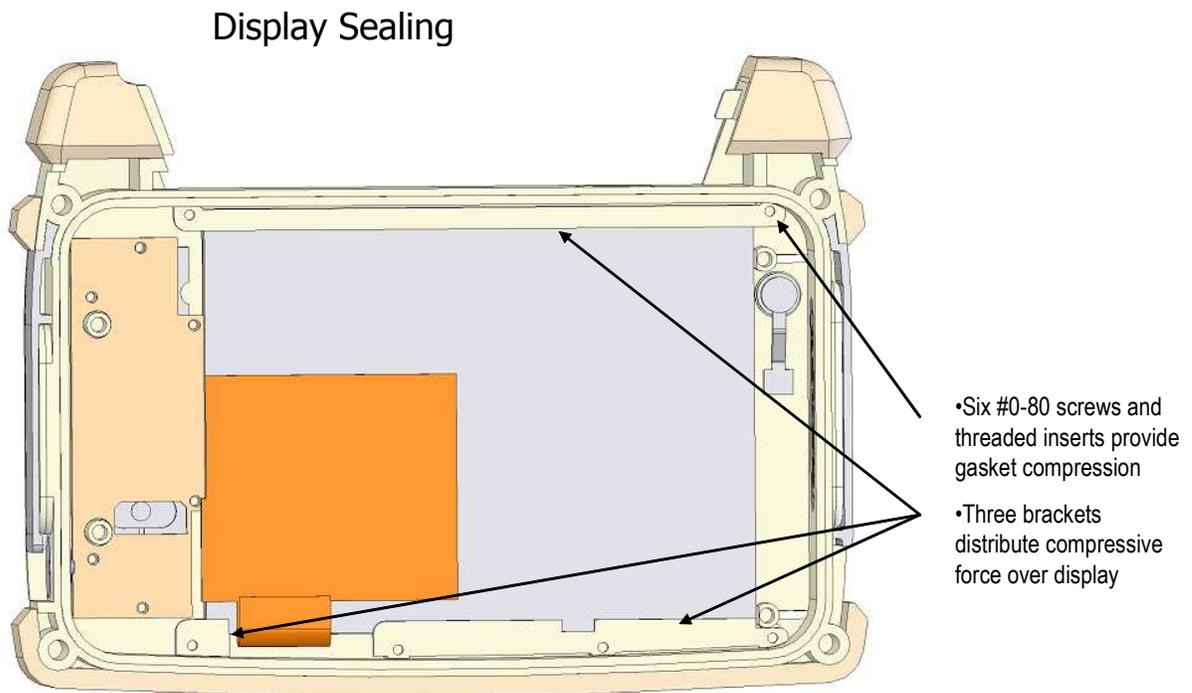


Figure 13: Sealing features for AMLCD display of Spiral 3.

On/off button Sealing

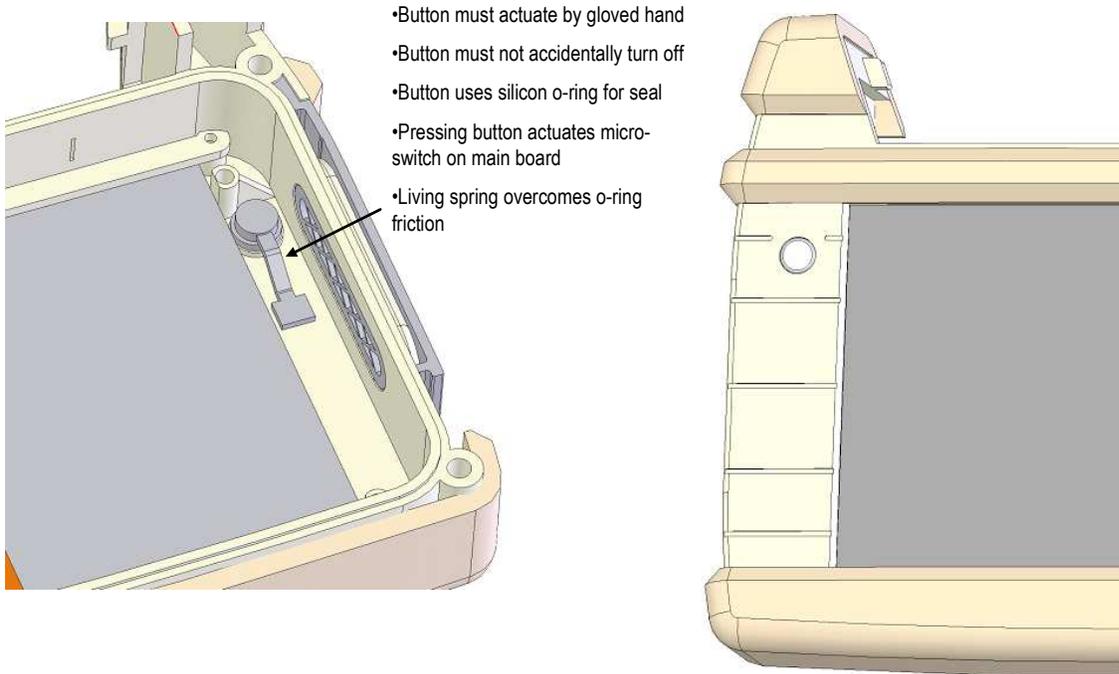


Figure 14: On/off button design considerations for Spiral 3.

On/off button Sealing

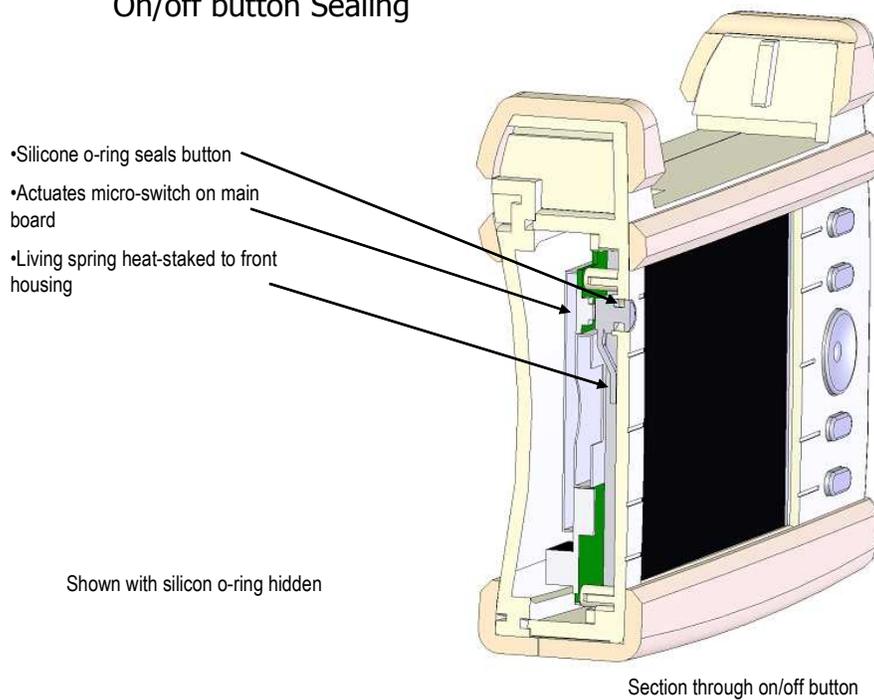


Figure 15: Design features for on/off button sealing for Spiral 3.

Reset button Sealing

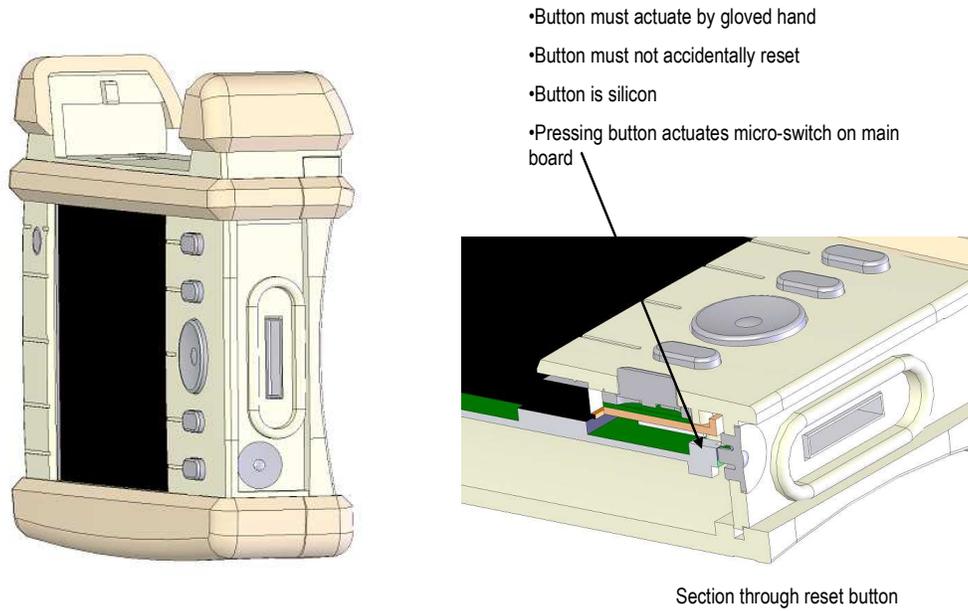


Figure 16: Reset button sealing design considerations for Spiral 3.

Keypad Sealing

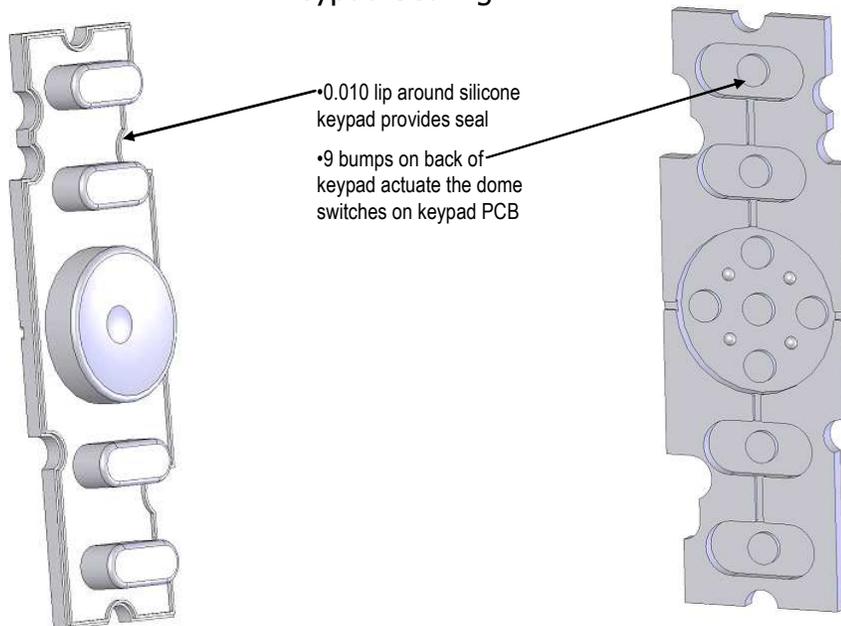


Figure 17: Keypad printed circuit board assembly features for sealing for Spiral 3.

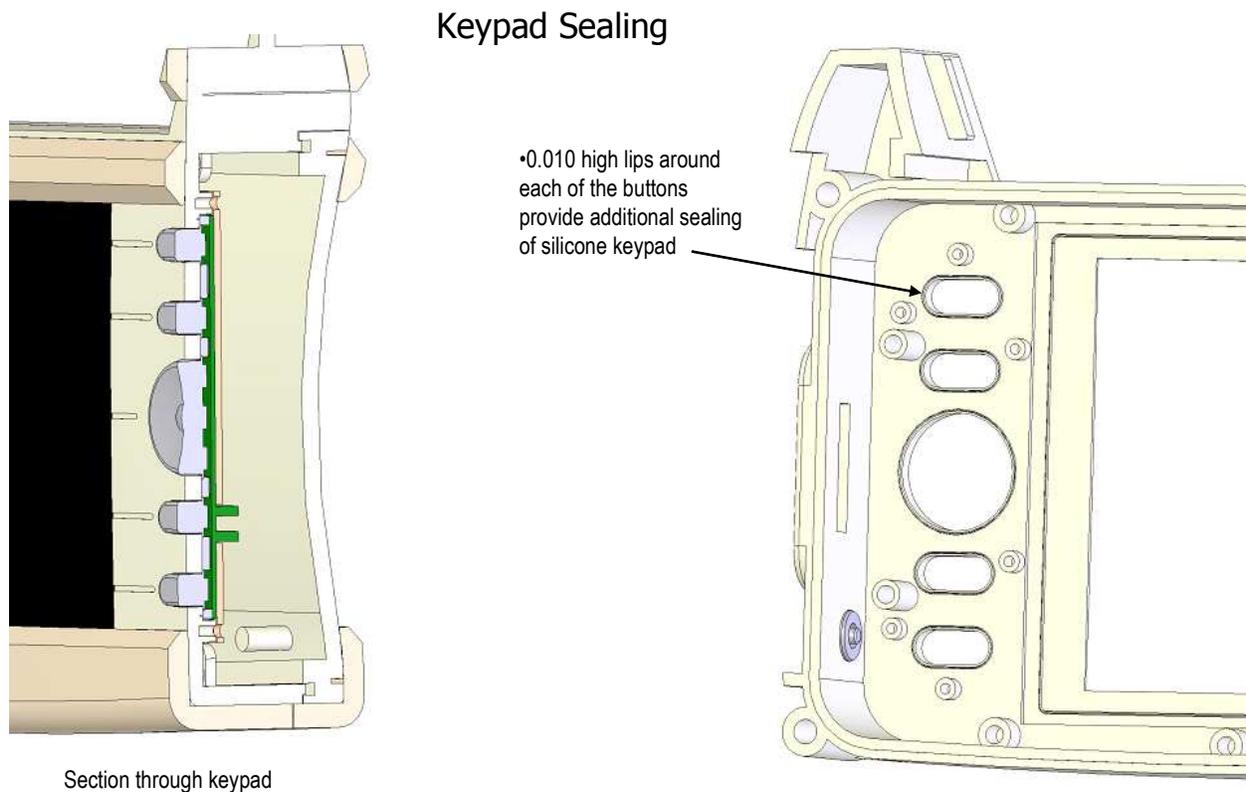


Figure 18: Keypad sealing features for Spiral 3.

3.1.4 Battery Life Testing for Spiral 3

The auxiliary external battery clip is shown with two AA batteries installed in Figure 19. Three different types of batteries were tested with this auxiliary battery unit to measure the relative amount of battery life extension provided by each. The increase in battery life for alkaline are included in Figure 20; nickel metal hydride (NiMH), Figure 21; and lithium ion, Figure 22. Test results as shown in Figures 20-22 indicate the following: (a) for the alkaline batteries, a 51% increase in battery life (4 hrs) with the iPAQ set to its slow, 500mA charge setting and a corresponding 16% increase (30 min.) with setting at 1000mA; (b) for the NiMH batteries, an 80% increase in battery life (7 hrs) with the iPAQ set to its slow, 500mA charge setting and a corresponding 70% increase (2.5 hrs) with the setting at 1000mA; and (c) for the NiMH batteries, a 135% increase in battery life (10 hrs) with the iPAQ set to its slow, 500mA charge setting and a corresponding 100% increase (3.5 hrs) with the setting at 1000mA. Based on these test results, any of the three battery types can be used with the Spiral 3 WAVE. Due to the almost universal availability of size AA alkaline batteries, the recommended approach was selected to be the use of common non-rechargeable alkaline batteries and two of these were supplied with each unit.



Figure 19: Auxiliary external battery clip for WAVE Spiral 3 with two AA batteries installed.

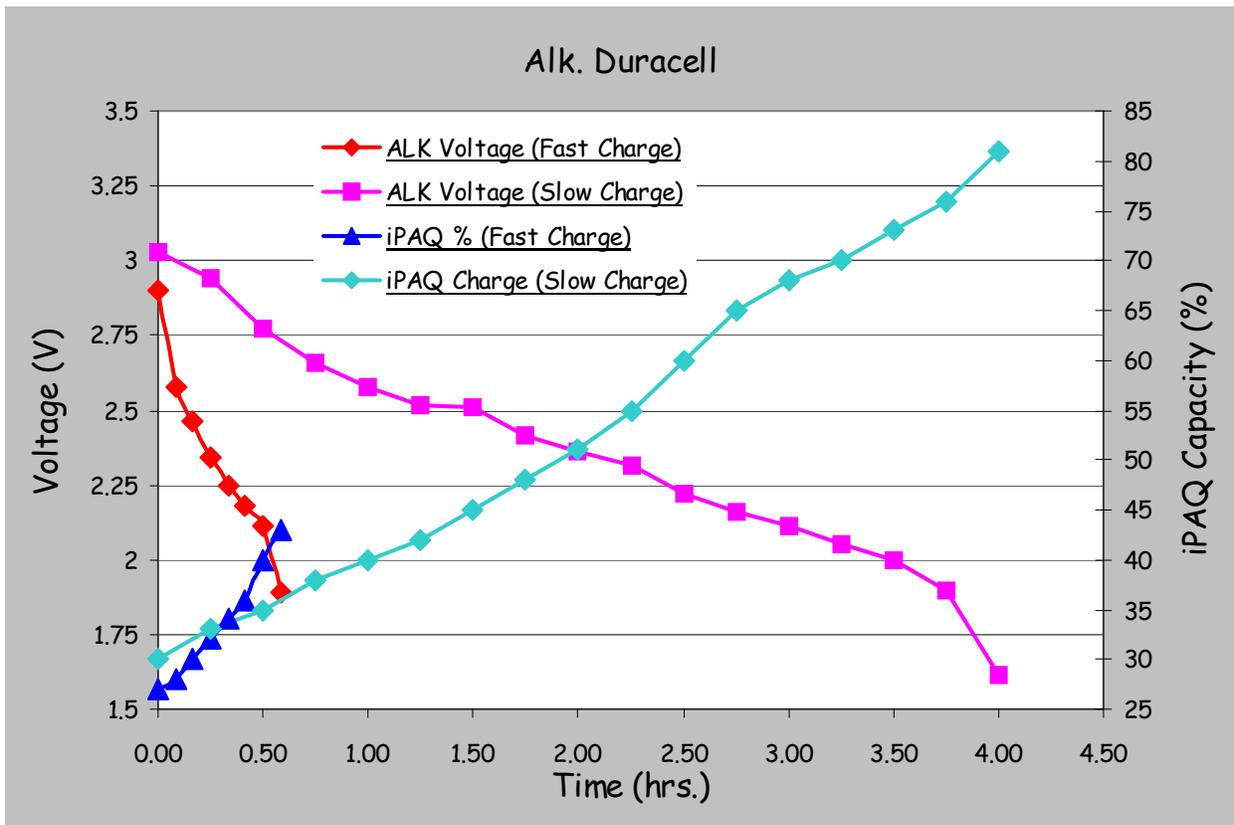


Figure 20: Battery life test results for Alkaline batteries

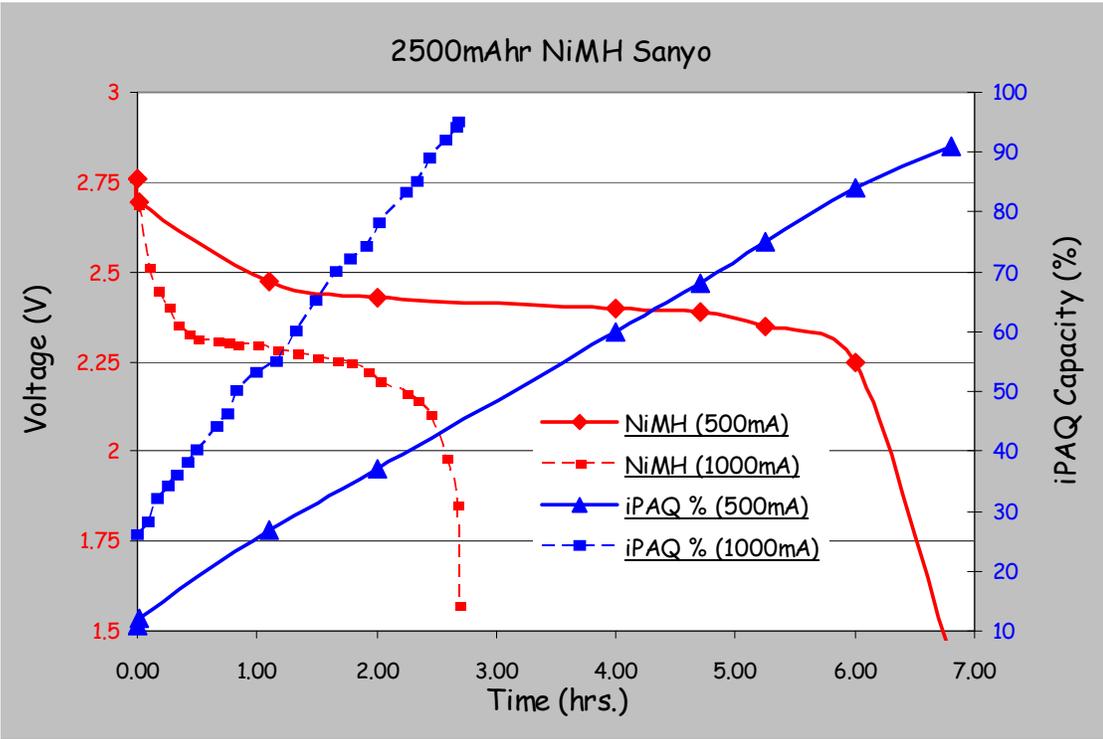


Figure 21: Battery life test results for NiMH batteries.

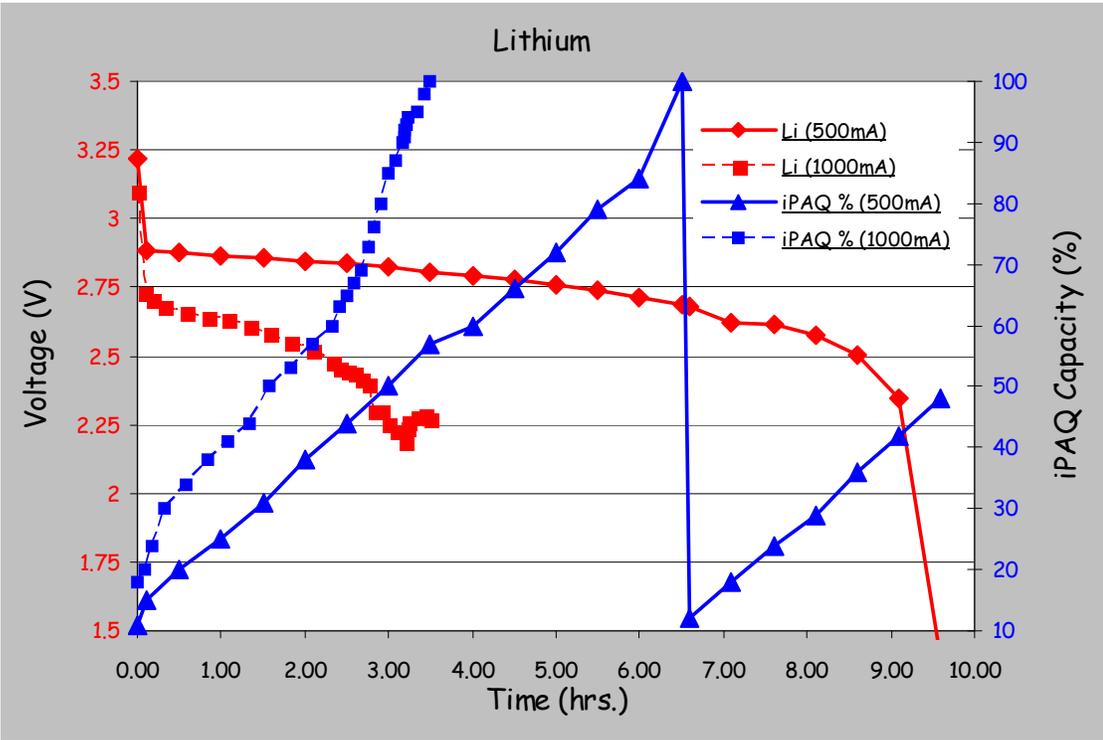


Figure 22: Battery life test results for lithium batteries.

3.1.5 Mechanical Testing for Spiral 3

Slingshot performed testing on the completed Spiral 3 units to verify that the design met the requirements for shock, handling, and water immersion.

Prior to the successful water immersion test, the prototype unit was subjected to a simulated test to ascertain the effectiveness of the sealing measures taken in the design. For this test, a clear unit was constructed and injected with a paste material which turns red upon contact with moisture. This technique allowed the designers to identify potential leakage areas and accommodate those areas in the final design. As a result of this preliminary testing the following design changes were implemented:

- Additional clamping was added along the shiplap seal
- Adhesive sealant was used to seal the display
- Adhesive sealant was used to seal the keypad

The final design passed all immersion and shock tests with no failures.

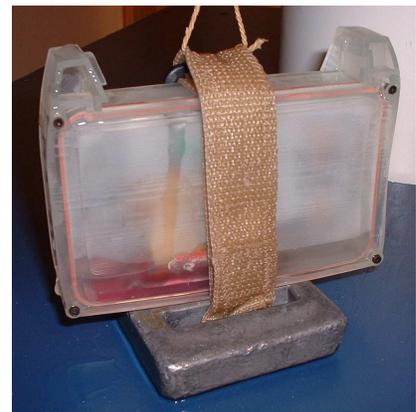
The setup for the water immersion test and the prototype unit are shown in Figure 23 below.



Water finding Paste:

- Changes color when exposed to water
- In large leak the paste will dye water and can help find leak

Weighted Wave on 3 ft tape



Example of a test run that leaked

Figure 23: Use of clear prototype and water paste during Spiral 3 immersion testing.

3.1.6 WAVE Spiral 3 Deliveries

The final Spiral 3 set of equipment as first delivered to the Air Force is shown in its cardboard shipping case with pink egg-crate foam in Figure 24a. Due to handling problems encountered in transit and during user field evaluations, a hardshell case was later procured and supplied by L3DS for each of the final 10 Spiral 3 units delivered. This hardshell case was a commercially procured hard plastic case suited for electronic devices with a custom black foam insert to hold the various elements of the WAVE 3 kit, as shown photographically in Figure 24b.



Figure 24a: First Spiral 3 WAVE delivery to AFRL.



Figure 24b: Final Spiral 3 WAVE delivery to AFRL in hardcase container.

3.2 Spiral 4 Wearable Display Device

The system architecture for the Spiral 4 WAVE device is shown in Figure 25. There are two main circuit boards packaged in the unit with separate battery adapter. The two circuit boards were supplied by Anders Electronics and consisted of a Windows CPU board and a custom baseboard. The display / touchscreen was a 2.8 inch diagonal viewing area AMLCD supplied by Anders. After test and evaluation, L-3 selected and supplied a night-vision-goggle (NVG) compatible filter material which could be affixed to the front surface of the display for use in NVG situations.

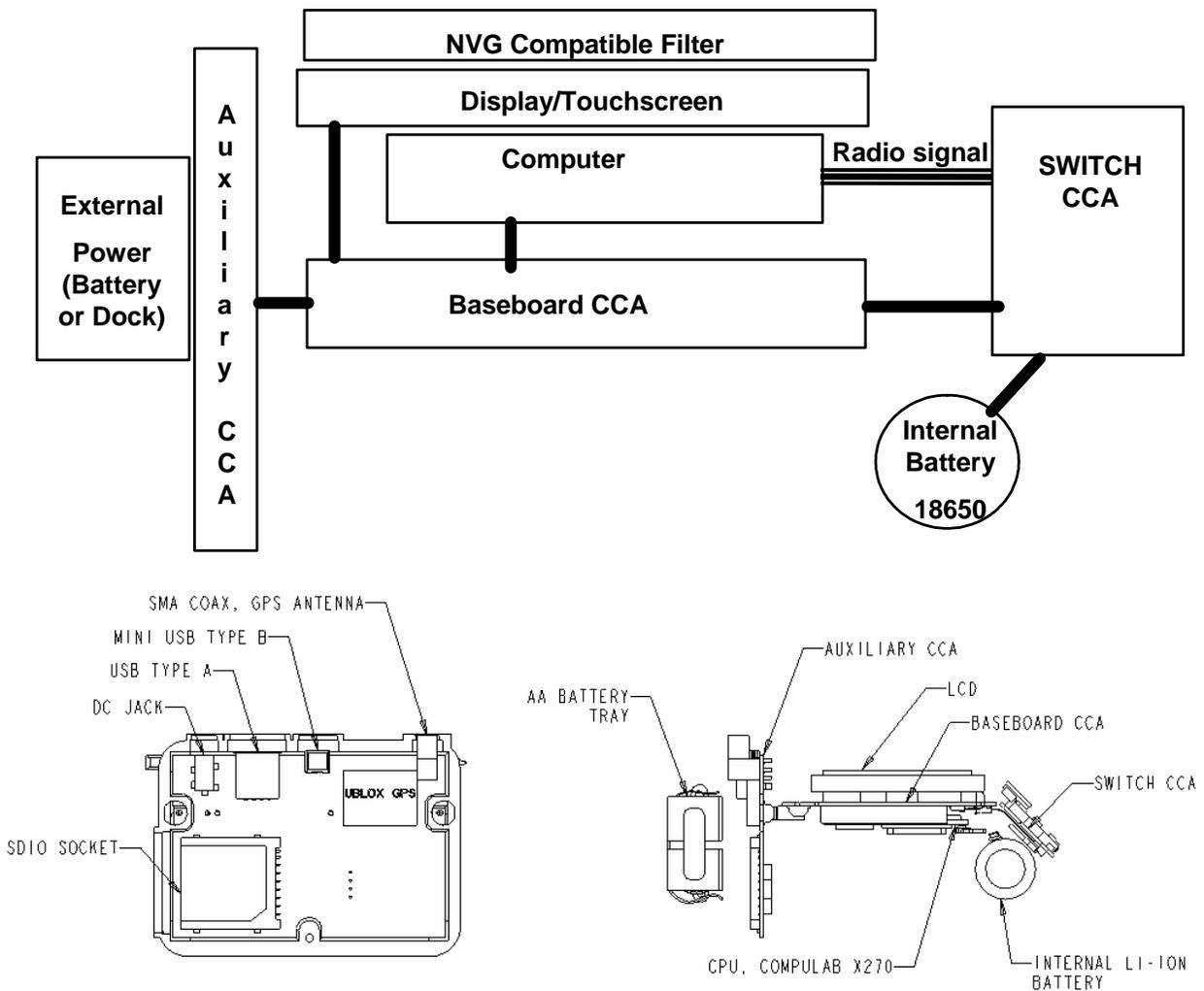


Figure 25: Spiral 4 system architecture.

3.2.1 Main Electronics for Spiral 4

The CPU board selected for use in Spiral 4 was a commercial off-the-shelf (COTS) ARM processor with on-card memory and interfaces. The block diagram for the CPU is shown in Figure 26. Key features of the Spiral 4 CPU include:

- Marvel(Intel) XScale PXA270 processor with clock speed of 520 MHz
- 128 MB SDRAM (synchronous dynamic random access memory)
- 512 MB NAND (not-and) Flash memory and 4MB NOR (not-or) Flash memory
- 802.11b Wireless LAN (local access network)
- USB1.1 Host and USB1.1 Host/Slave
- Industrial Temperature -40°C to +85°C
- 0.2 to 3 Watts power consumption
- 325 million instructions per second (MIPS)

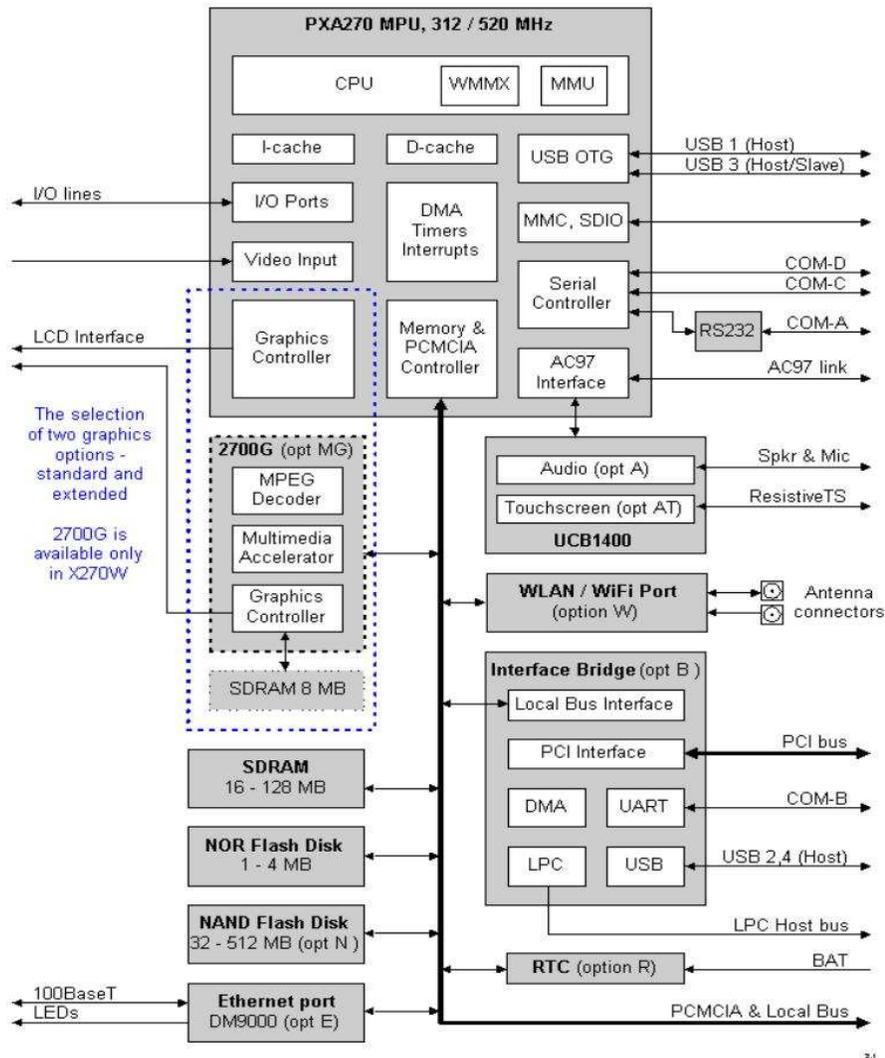


Figure 26: Spiral 4 CPU block diagram

Anders designed a baseboard (auxiliary circuit card) to connect to the CPU board at a right angle and provide room for additional memory, embedded GPS functions, and other housekeeping functions. With the baseboard concept, future spirals can add functionality by modifying the baseboard, while leaving the rest of the unit intact, thus simplifying upgrades. This auxiliary board is mounted inside the separate battery adapter with connection to the CPU. This auxiliary card is shown in Figure 27.



Figure 27: Baseboard (auxiliary circuit card) for Spiral 4.

3.2.2 Battery Adapter for Spiral 4

In a similar fashion to the design chosen for the Spiral 3 WAVE, the Spiral 4 design utilized the concept of an easily removable and replaceable battery adapter to provide extended wireless life for the unit. The basic mechanical concept for the battery adapter is shown in Figure 28.

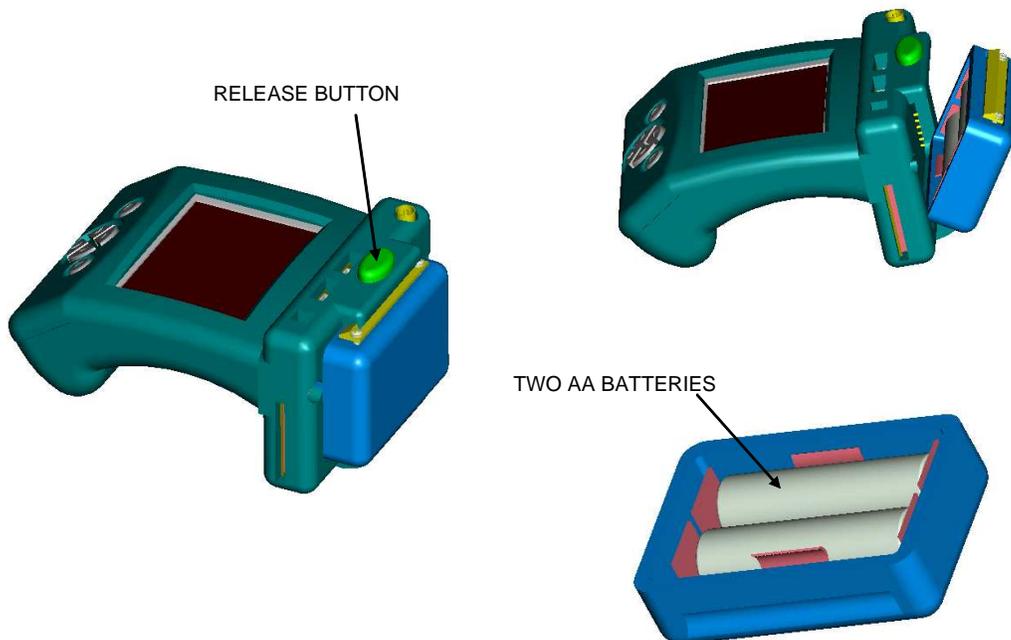


Figure 28: Spiral 4 battery concept

Following electrical testing of different battery types, the Samsung ICR18650 battery was chosen as shown in Table I. This battery offers 2400mAh of current, yet is packaged in the same form factor as batteries with much less capacity. The Samsung ICR18650 Li-ion battery is located under the operator keys of the Spiral 4 housing. A snap-on holds the two AA batteries comprising the auxiliary power source, as shown in the bottom right portion of Figure 28.

Table 1: Battery selection comparison for Spiral 4.

	Current Battery Selection Samsung ICR18650-24e	Original Battery Selection Saphion IFR18650e
Nominal Capacity	2400 mAh (~7.7 Wh)	1400 mAh (~4 Wh)
Charge Voltage	4.2 V	3.65 V
Nominal Op. voltage	3.7 V	3.2 V
Max. Continuous Discharge	4.4 A	2.8 A
Discharge Cut-off	2.75 V	2.5 V
Operating Temp	-20 to 60 °C	-10 to 50 °C
Weight	46 g	38 g
Diameter	18 ± 0.3 mm	18.4 mm MAX

3.2.3 Night Vision Goggle Compatibility Testing for Spiral 4

The Spiral 4 device was required to be able to operate with a night vision goggle (NVG) compatible filter applied to the AMLCD display. L-3 obtained samples of night vision imaging system (NVIS) filters from different manufacturers and evaluated their spectra to determine the best selection for delivery with Spiral 4 devices. The design goal for the filter was to be compatible with NVIS Class A systems. The DoD published goal for NVIS Class A systems is for total energy above 700 nm to be no more than 0.5% of the total energy between 350 and 930 nm. The cut-off is to be between 600 and 700 nm, and as close to 600 nm as possible.²

L-3 obtained a sample filter from Eaton, a Neutral Green A, part number 3003-NV3NS-1. Figure 29 provides a spectral comparison of this filter material with a common NVIS Coherent filter in use on another program. The Eaton Neutral Green A filter had a non-specular surface that improved contrast, specular, and diffuse reflectance. The non-specular surface was mounted to face the user. This Eaton filter caused a ~35% loss in transmission (from 67.0 to 43.4 fL for a white test screen) and shifted the v' chromaticity by ~0.5 for white; however, the image was legible through an NVG. This Eaton Neutral Green A filter failed both NVIS A and NVIS B compatibility tests and was not selected for use with WAVE Spiral 4.

Next, a different Eaton covert NVIS filter, Gray, part number 3003-NV50-1 was tested. With this filter the display appeared completely opaque in the visible region, but when viewed through NVIS goggles, the light from the display was bright. During this test, the LCD backlight was not adjustable. The filter did make the figures and icons a bit blurred and difficult to read. A thinner filter may be the best choice. The results of these spectral scans are shown in Figure 30.

² DoD Interface Standard, Lighting, Aircraft, Night Vision Imaging System (NVIS) Compatible, MIL-STD-3009, 2 February 2001 (supersedes MIL-L-86762A). http://www.dodsbir.net/sitis/view_pdf.asp?id=DOD-STD-3009.pdf

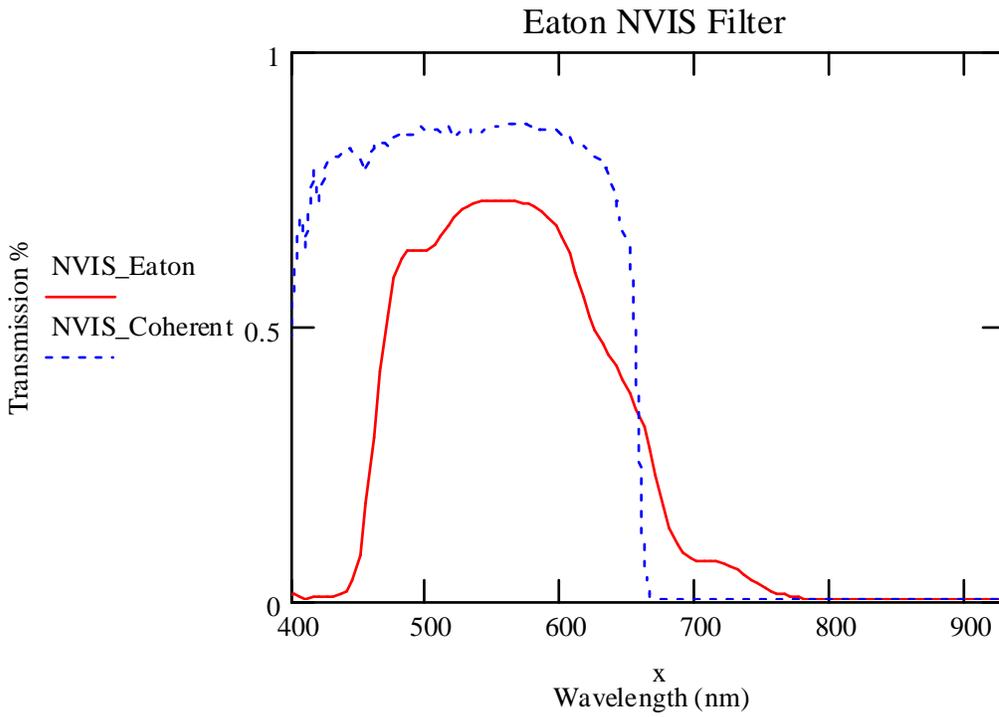
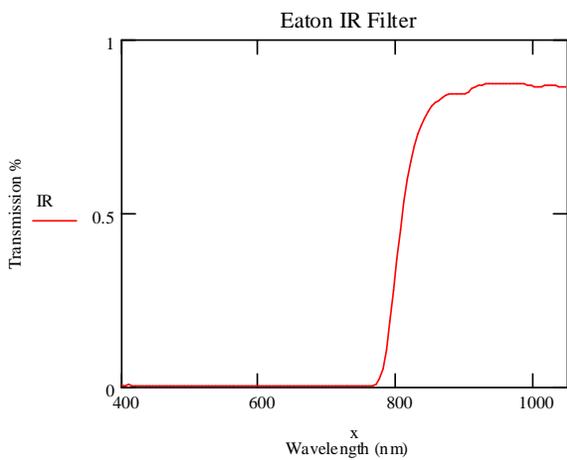


Figure 29: Spectral scan comparison with a common NVIS filter.

Spectral scan of IR filter



Spectral scan of display with IR filter:

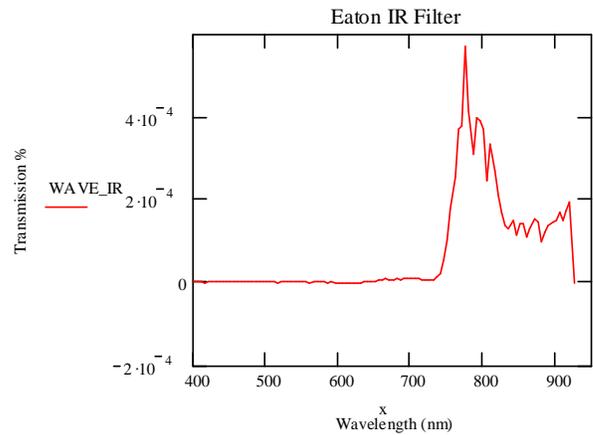


Figure 30: Spectral scan results of covert infrared (IR) filter material.

3.2.4 Mechanical Packaging of Spiral 4

Spiral 4 was intended as a laboratory demonstration device (TRL 4), so the chassis was fabricated from plastic using a stereolithographic assembly (SLA) process. The SLA packaging is very rigid and can withstand repeated handling for evaluations, but is not suitable for high temperature environments or immersion in liquids. The primary features of the main housing with inputs and outputs shown are illustrated in Figures 28 and 31. An exploded view of the main housing is illustrated in Figure 32.

Even though the requirement for Spiral 4 did not include the immersion testing as for Spiral 3, consideration was made for sealing and waterproofing the unit as well as the SLA material allowed. This aspect of the design process was addressed to make future iterations of the WAVE easier to adapt to more rugged environments and to higher TRL levels. Figures 33 and 34 show the design features of the Spiral 4 SLA packaging that provide a measure of seal and waterproofing.

3.2.5 Test and Delivery of Spiral 4

Following completion of the baseboard printed circuit design, the baseboard and main CPU board had to be integrated with the Windows CE operating system, the 2.8-in. AMLCD, and the touchscreen before delivery. Figure 35 shows the unit in final integration at Anders Electronics prior to shipment to L-3 DS for delivery to the Air Force.

Two units were delivered to AFRL on December 20, 2007 and the eight remaining units were delivered the week of February 20, 2008. These units are currently undergoing user evaluation by the Air Force. Figure 36 is a photograph of one of the Spiral 4 units as delivered to AFRL in its protective black hardcase shipping/storage container.

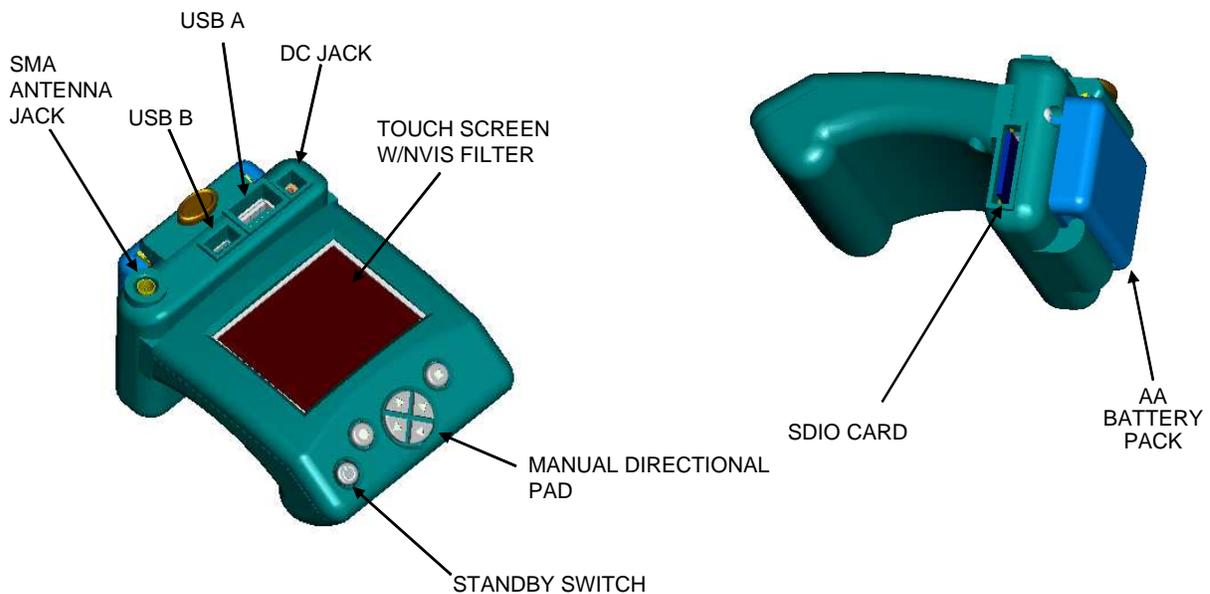


Figure 31: Main housing and adapter configuration for Spiral 4.

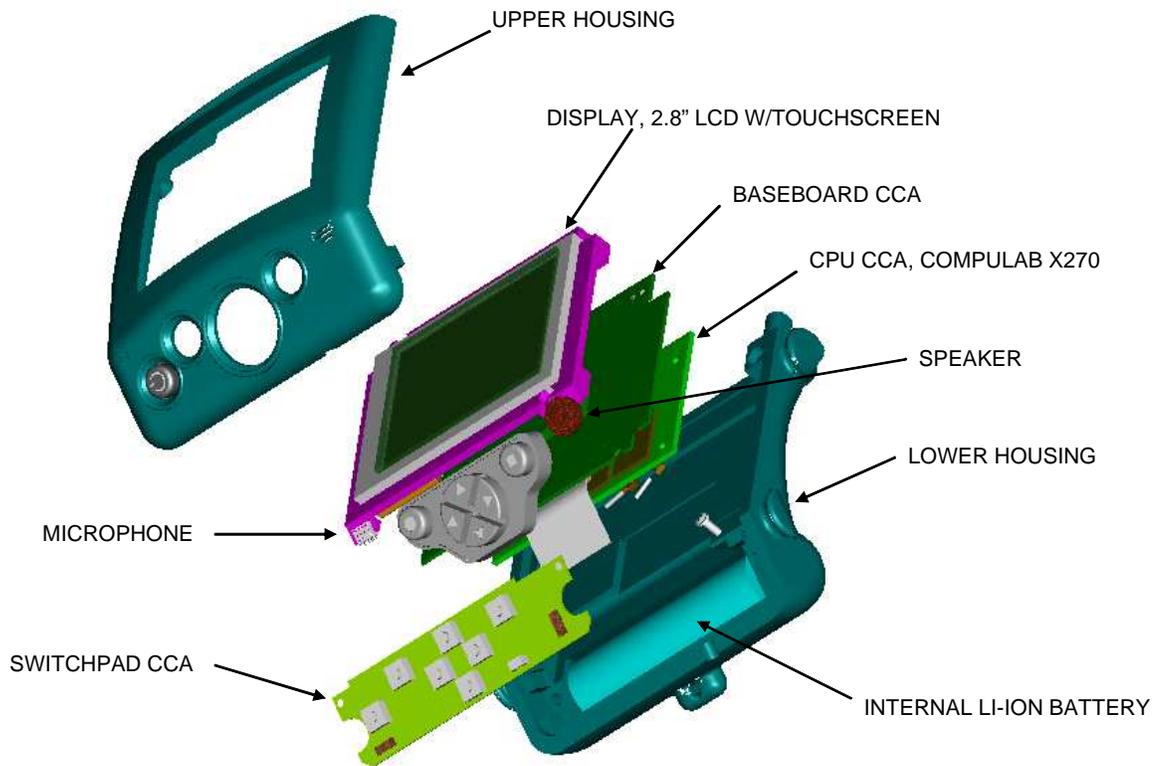


Figure 32: Exploded view of Spiral 4 main housing assembly.

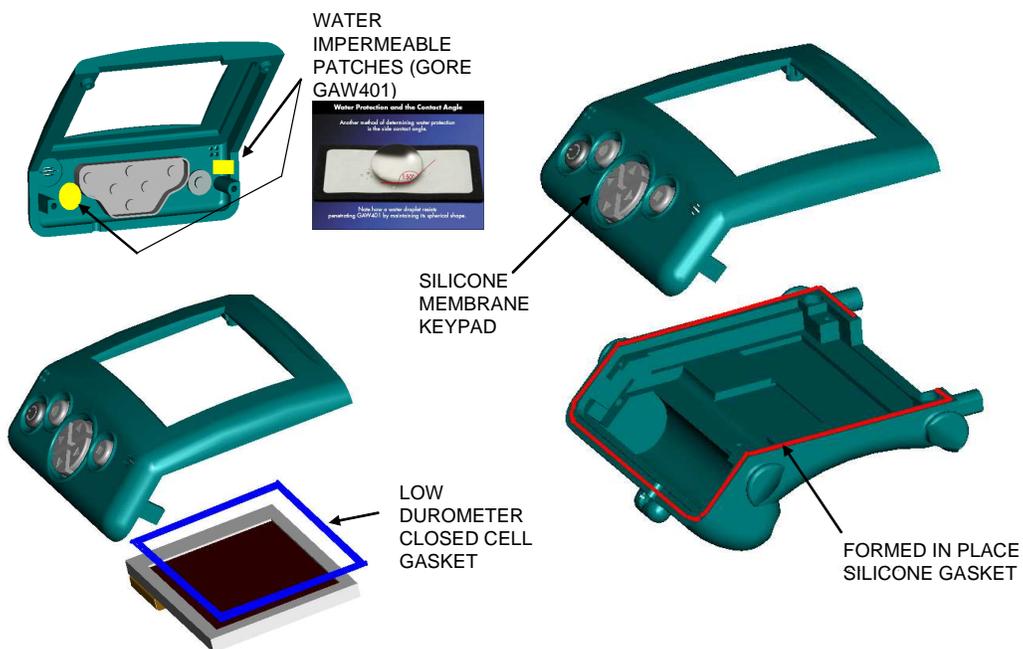


Figure 33: Sealing and waterproofing design features of the Spiral 4 main housing.

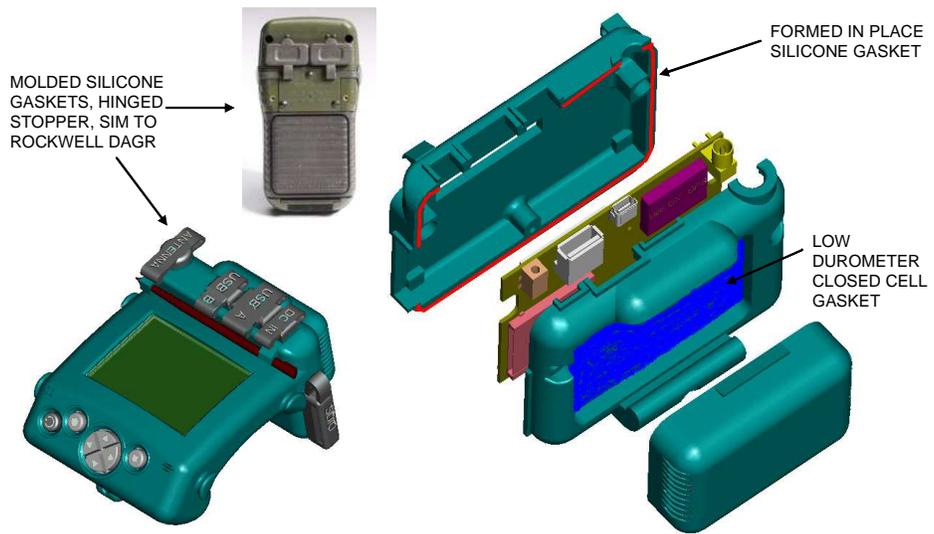


Figure 34: Sealing and waterproofing design features of the Spiral 4 adapter housing.



Figure 35: Spiral 4 electronics in hardware/software integration at Anders (August 2007).



Figure 36: WAVE Spiral 4 kit as delivered to AFRL.

3.3 Technology Roadmap

During this Phase 2 of the modified contract, L-3 DS continued to track developments in the field of wearable and portable electronics. The purpose of the roadmap task was to maintain a plan-ahead path which could be used to guide future spiral requirements for wearable communication devices utilizing the flexible display technology when it is developed.

The desired functions of the WAVE devices include wireless communications, common user electrical interfaces, video and imagery functions, secure communications, and user input device technologies. Many of these desired functions were determined by feedback given by the Air Force user community, particularly the 720th Special Tactics Group at Hurlburt Field FL and other knowledgeable users.

Figure 37 illustrates a possible incremental spiral development path for FDICD functionality. The Spiral 3 and Spiral 4 WAVE devices produced during Phase 2 of this contract satisfy the first two spirals indicated on the chart under the “Integrated Communications” heading.

Figure 38 shows the timeline and programmatic coordination of funding sources between the Air Force, Army, L-3 DS, and other partners to enable progressive development steps advancing the enabling technologies required to deliver a suitable FDICD device to the warfighter.

FLEXIBLE DISPLAY AND INTEGRATED COMMUNICATION DEVICE ROADMAP SPIRALS							
Flexible Display Technology	4" QVGA mono Conformable 500 hr - driven 3K hr - shelf	4" QVGA color Steel substrate 500 hr - driven 3K hr - shelf	4" QVGA color Conformable 500 hr - driven 3K hr - shelf	4" QVGA color Conformable 500 hr - driven 3K hr - shelf Integrated drivers		6" VGA color Conformable 1K hr - driven 5K hr - shelf Integrated drivers	8-10" SVGA rollout covert display mode
Rollable display development					4" VGA conformable covert display mode	6" VGA wrap-around covert display mode	8-10" SVGA rollout covert display mode
Integrated Comm (IC)		<u>SPIRAL 3</u> WiFi 802.11b WiFi Keyboard NTSC video Display drivers	<u>SPIRAL 4</u> WiFi 802.11b Foldable Keyboard NTSC video Display drivers GPS	WiFi 802.11b Foldable Keyboard NTSC video Integrated drivers GPS Software radio Encryption	WiFi 802.11g Foldable Keyboard NTSC video Integrated drivers GPS Software radio Encryption Camera Microphone	WiFi 802.11g Foldable Keyboard NTSC video Integrated drivers GPS Software radio Encryption Camera Microphone	WiFi 802.15.3 WiFi 802.11g Foldable Keyboard NTSC video Integrated drivers GPS Software radio Encryption Camera Microphone

Figure 37: Spiral development technology roadmap for FDICD devices.

Flexible Display and Integrated Communication Device (FDICD) Timeline

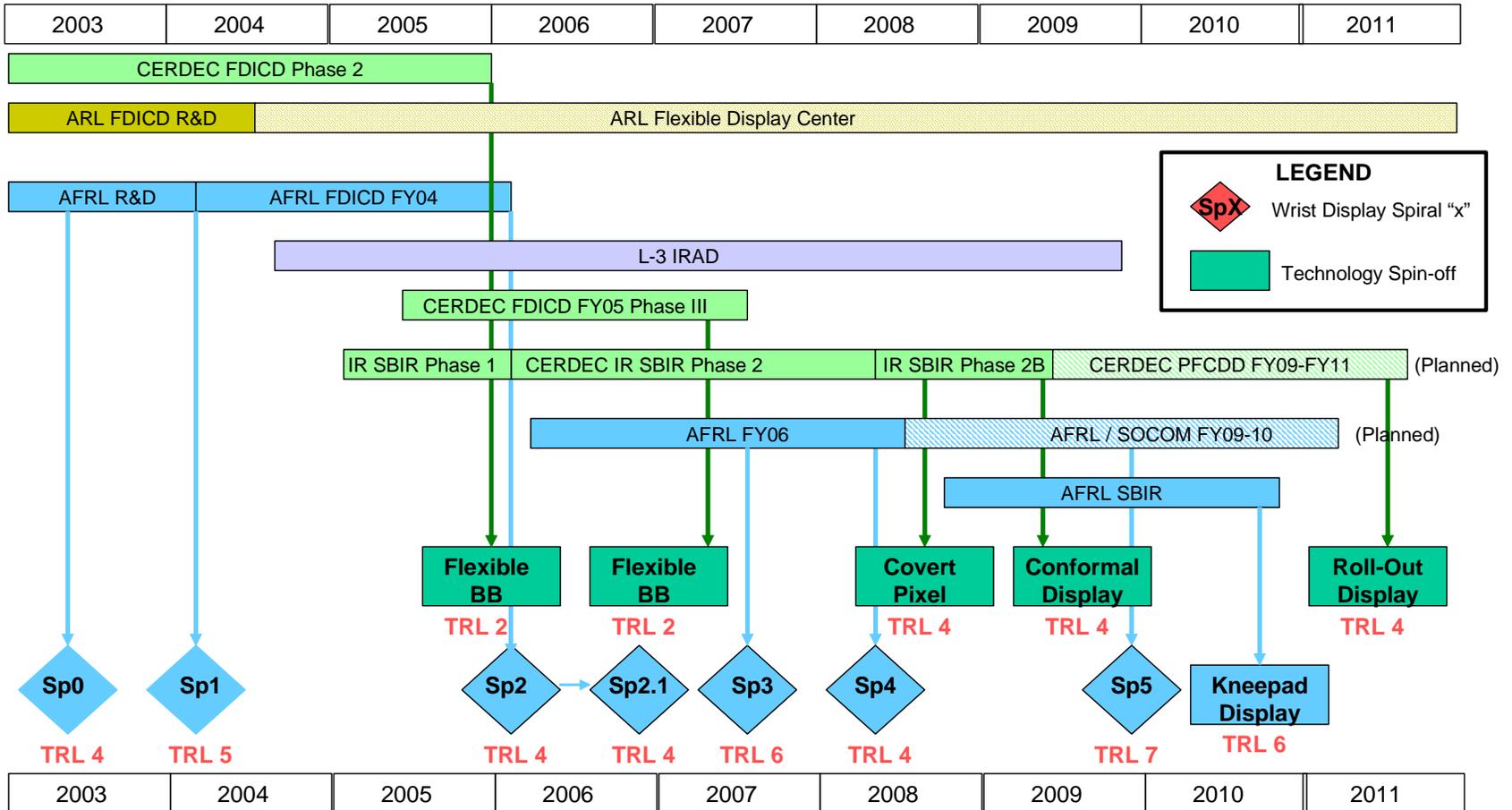


Figure 38: Spiral development technology funding roadmap for FDICD (Sp = Spiral).

4. DISCUSSION

4.1 Spiral 3 Wrist Display

In this task L-3 was required to raise the TRL level of the wrist device to at least TRL 6 for evaluation under real world conditions by Air Force personnel in real or simulated military environments. In order to accomplish this, the following modifications were accomplished for the ruggedized HP iPAQ PDA approach: the SLA enclosure was replaced with an injection-molded housing (IMH) for more ruggedness and seals were incorporated so that the unit could withstand immersion in water; the operator's pushbutton functions on the PDA were implemented on the outside of the housing to allow use; environmental confidence testing, such as vibration, temperature, shock, and drop test were performed and documented in accordance with MIL-STD-810E; functioning auxiliary battery clipon was included in the housing for extended missions; an optimized wide Velcro cinch strap wrist band with protective fabric covering as designed for one-handed donning/doffing with a tethered stylus; key functionalities of the HP iPAQ PDA were retained (wireless Bluetooth and WiFi IEEE 802.11b; Windows Mobile 5.0 operating system, and touchscreen).

Ten prototype WAVE Spiral 3 (TRL 6) field evaluation kits were delivered to the Air Force. Two of these were then delivered by the Air Force to its FDICD partners at ARL and CERDEC.

Work is underway now to identify users and applications which could benefit from the ability to have rugged processing worn on the body.

4.2 Spiral 4 Wrist Display

This task required L-3 to develop and deliver a Spiral 4.0 wearable display system with increased integrated communication capability. This spiral had more functions than the Spiral 3.0 device. L-3 incorporated the following new functions into this Spiral 4.0 device: integrated (embedded) GPS; NVIS Class A night vision compatible filter for covert operation; and increased memory capacity to 1 GB. L-3 investigated, but did not include, several other features as follows: digital camera; biometric sensor for security identification; alternate methods of power generation (e.g. solar cells, mechanical); and high-speed low-power processor (such as the HyperX).

Ten prototype WAVE Spiral 4 (TRL 4) laboratory evaluation kits were delivered to the Air Force, with two of these intended for delivery by the Air Force to the FDICD partners at ARL and CERDEC.

The Spiral 4 devices were demonstrated to meet the functional requirements of the statement of work. Future spiral developments of this device should take into account laboratory and user feedback as to the suitability of the devices for the intended mission.

4.3 Updated Technology Roadmap

The technology roadmap task which was begun during Phase 1 was continued in Phase 2 under the modified contract. The focus of this contract was the development of integrated communication and processing functions. As shown in the funding roadmap of Figure 38 on the previous page, several funding sources have been combined to advance the device through successive levels of integration.

A combination of AFRL-funded research, supplemented with L-3 funded development, has taken the WAVE device from the first Spiral 1 delivered in 2004 to the latest version, Spiral 4, delivered in 2008. Spiral 1 represented a device which functioned solely as a display monitor and allowed only wired operation. Spiral 4 represents a device which contains a processor capable of executing a Windows-compliant operating system as well as running applications solely on the wrist. It supports both wired and wireless operation and is capable of running under batteries.

Table 2 shows the progress of the WAVE device through successive spiral iterations, which were guided by the results and investigations necessary in defining the technology roadmap.

Table 2: Comparison of features across WAVE spirals.

Feature	Spiral 1.0	Spiral 2.0	Spiral 2.5	Spiral 3.0	Spiral 4.0
Year	2004	2005	2006	2007	2008
Program	AFRL Task Order	FDICD Phase 1	FDICD Phase 1	FDICD Phase 2	FDICD Phase 2
S&T (\$)	100K	146K *	583K **	500K	500K
Approach	Monitor	Custom Design	Rugged PDA	Rugged PDA	Custom Design
Subcontractors					
Design	L-3 DS	L-3 DS	SPDG	SPDG	L-3 DS
Processor	L-3 DS	L-3 DS	HP	HP	Anders / Valigent
Software	N/A	N/A	Microsoft	Microsoft and Senscom (Dashboard)	Microsoft and Embedded Solutions
Hardware					
Display	PrimeView	3-5 Systems	Toppoly	Toppoly	TPO
Resolution	160 x 234	qVGA	qVGA	qVGA	qVGA
Processor	N/A	Freescale MX21	HP iPAQ hx2490	HP iPAQ hx2495	Marvel PXA270
Memory	None	32 MB	256 MB	512 MB	1 GB
Signal Mode	Wired only	Wired and wireless	Wired and wireless	Wired and wireless	Wired and wireless
Power Mode	Cable only	Cable and battery	Cable and battery	Cable and battery	Cable and battery
Wireless	None	802.11b	802.11b	802.11b	802.11b
USB	None	None	None	USB 2.0	USB 1.1
Geolocation	None	None	None	None	GPS
Mounting					
Method	Hooks	Not delivered	Dual straps	Single wide cinch strap w/ Velcro attach/detach	Single wide band with dual elastic straps
Required for operator donning & doffing	2 hands with multiple cable attachment	N/A	2 hands	1 hand	2 hands

Notes: * L-3 DS cost share on Phase 1 of FDICD contract. Spiral 2 was not delivered to AFRL.
 **L-3 DS IRAD effort

5. CONCLUSIONS

During this Phase 2 of the FDICD program, L-3 and the Air Force developed two versions of wearable computing devices which are capable of providing real-time video, maps, and other necessary applications to the user in a small ergonomic form-factor. These two versions, WAVE Spirals 3 and 4 are illustrated in Figures 39 and 40, respectively. The Spiral 3 device is at TRL 6 and is ready for full military qualification testing and upon completion of that testing would be suitable for use in deployed systems.

The Spiral 4 device is at TRL 4 and represents a very adaptable platform for evaluating Air Force, Army and Navy applications and for incorporating additional communications capability such as cameras, alternate antennas, and tactical mission applications. The units can also be used as testbeds for newer battery capabilities and NVIS filter compatibility testing.

The benefits of the technology to the warfighter are apparent in the small form-factor and ruggedness of these devices. Continued development is required to advance the technology to the level of maturity needed by today's forces.



Figure 39: WAVE Spiral 3 as delivered to the Air Force for evaluation.



Figure 40: WAVE Spiral 4 device and wrist strap as delivered to the Air Force for evaluation.

6. RECOMMENDATIONS

This AFRL contract initiated development of a flexible display and integrated communications display capability. This Phase 2 of the contract continued advances in the design and packaging of wearable computing. The resulting devices offer the military a small form-factor display which will ultimately lessen the load that the dismounted warfighter presently carries. Two recommendations for further work are made here regarding user feedback and functionality optimization.

The first recommendation is to obtain feedback from military users on benefits and shortfalls of the technology. The work performed under this contract developed two devices which can be considered as platforms for further investigation into needed interfaces and applications. The ultimate authority for the design and for the applications which will run on the devices is the Air Force and Army user. It is recommended that both the Spiral 3 and Spiral 4 devices be presented to representative warfighter units for their suggestions, criticisms, and insights.

The second recommendation is to continue efforts to merge the integrated communication electronics with flexible display technology when appropriate. These devices are intended to eventually join with research being accomplished in the field of conformal or flexible displays. These displays may use AMOLED or electrophoretic or AMLCD frontplanes, but in either case, the small size of the electronics developed in this program will benefit the resulting FDICD.

7. SYMBOLS, ABBREVIATIONS, AND ACRONYMS

AFRL	Air Force Research Laboratory (controls all S&T funds in the USAF)
AM	Active matrix (type of electronics backplane in high quality flat panel displays)
AMLCD	Active matrix liquid crystal display (dominant type of flat panel display device)
AMOLED	Active matrix organic light emitting diode (new type of flat panel display)
ARL	Army Research Laboratory, a part of RDECOM
ARM	Industrial provider of 32-bit embedded RISC microprocessors, http://www.arm.com/
BAO	Battlefield Air Operations
BB	Bread Board
Blue	Light in wavelength range of roughly 440-490 nm
CCA	Circuit card assembly
CE	Compact Edition (version of Windows operating system for handheld devices)
CERDEC	Communications Electronics Research and Development Engineering Center, a part of RDECOM
CF slot	Compact Flash slot, accommodates PCMCIA adapter/expander
CM-X270L	Processor board used in Spiral 4 WAVE
COTS	Commercial-off-the-shelf
CPU	Central processing unit
FDICD	Flexible Display and Integrated Communication Devices
GB, GByte	Gigabyte (one billion bytes of memory)
Gen 3 NVIS	NVIS intensifier tube technology that uses a gallium arsenide photocathode and multichannel plate (MCP) intensifier. Gen 3 tubes are more sensitive than Gen 2 and are used in NVIS for aviation.
GIS	Global imaging system
GPS	Global positioning system
Green	Light in wavelength range of roughly 520-570 nm
HASC	House Armed Services Committee
HP	Hewlett Packard
iPAQ	HP Pocket PC used in Spiral 3 WAVE (HP iPAQ hx2490 Pocket PC) ³
IMH	Injection-molded housing (more rugged than SLA rapid prototyping housing)
IR	Infra-red (light with wavelengths in the range 750 nm – 1 mm)
L-3 DS	L-3 Communications Display Systems in Alpharetta GA
LAN	Local area network
LCD	Liquid crystal display (typically refers to TFT-AM-LCD, unless stated otherwise)
Li-ion	Lithium-ion (type of battery)
mA	Milliampere (measure of current)
MB	Megabyte (one million bytes of memory)
MIPS	Million instructions per second (measure of processor throughput)
MS Mobile 5	Microsoft operating system used on Spiral 3 WAVE (embedded in HP iPAQ)
NAND	Not-and (type of flash memory)
NiMH	Nickel metal hydride (type of commercial battery)

³ Details on the HP iPAQ hx2490 Pocket PC are available on the Hewlett Packard website:
<http://search.hp.com/query.html?lang=en&submit.x=6&submit.y=4&qt=hx2490&la=en&cc=us>

NOR	Not-or (type of flash memory)
NTSC	National Television Standards Committee analog TV system used in U.S., Canada, Japan, South Korea (standard resolution TV broadcast (525 lines with first 480 for image and last 45 for CRT vertical blanking interval; even/odd lines written in two interlaced fields at 2 fields/frame, 59.94 fields/s) 336 spots/line; white point & RGB color space in CIE1931(x,y) for NTSC1979: D65 W(0.31271,0.32902) & R(0.63,0.34), G(0.31,0.595), B(0.155,0.07). ⁴
NVG	Night vision goggles
NVIS	Night vision imaging system ^{2,5}
NVIS Class A	Refers to a 625 nm minus-blue filter added to a Gen 3 NVIS to reduce its sensitivity to visible light below the red band. Class A NVIS photoresponse is one percent at 595 nm.
NVIS Class B	Refers to a 665 nm minus-blue filter added to a Gen 3 NVIS to reduce its sensitivity to visible light, including most of the red band. Class B NVIS photoresponse is one percent at 625 nm.
OLED	Organic light emitting device
PARC	Palo Alto Research Corporation
PC	Personal computer
PCB	Printed circuit board
PCMCIA	Personal Computer Memory Card International Association
PDA	Personal digital assistant (HP hx2490 series iPAQ used for Spiral 3 WAVE)
Poly-Si	Polysilicon (material used in fabrication of display backplanes)
PRDA	Program Research and Development Announcement
PWB	Printed wiring board
qVGA	Quarter Video Graphics Array (320 pixels by 240 lines of resolution on display)
QVGA	Same as qVGA within this report
RDECOM	U.S. Army Research, Development and Engineering Command (all Army S&T)
Red	Light in wavelength range of roughly 625-740 nm
RISC	Reduced instruction set computing
RS170	Video signal developed by the Engineering Industries Association (EIA) in 1957 as a standard for monochrome (black and white) television studio facilities
SBIR	Small Business Innovative Research program
SDIO	Serial data input output port (a commercial standard form factor for peripherals)
SDRAM	Synchronous dynamic random access memory
SLA	Stereolithographic assembly (rapid prototyping tool for plastic packaging)
SPDG	Slingshot Product Development Group in Lawrenceville GA
SVGA	Super Video Graphics Adapter (800 pixels by 600 lines of resolution on display)
TFT	Thin-film transistor (semiconductor device used implement the active matrix backplane that drives pixels in AMLCDs, AMOLEDs & other AM technologies)
TRL	Technology Readiness Level ⁶
TRL #	TRL 1 – Basic principles observed and reported TRL 2 – Technology concept and/or application formulated

⁴ http://en.wikipedia.org/wiki/RGB_color_space and http://en.wikipedia.org/wiki/White_point (accessed 22 June 2008).

⁵ *Digital Avionics Handbook*, Cary R. Spitzer, Edior (CRC Press, 2006).

⁶ John C. Mankins, "Technology Readiness Levels," A White Paper, 5 pp. (NASA Advanced Concepts Office, 6 April 1995).

- TRL 3 – Analytical and experimental critical function and/or characteristic proof-of- concept
- TRL 4 – Component and/or breadboard validation in laboratory environment
- TRL 5 – Component and/or breadboard validation in relevant environment
- TRL 6 – System/subsystem model or prototype demonstration in a relevant environment (air, land, sea, space, cyberspace)
- TRL 7 – System prototype demonstration in a fielded/combat environment
- TRL 8 – Actual system completed and qualified through test and demonstration in a fielded/combat environment
- TRL 9 – Actual system field-proved through successful use in combat operations

UK	United Kingdom
USB	Universal Serial Bus (used to attach peripherals to a processor)
VGA	Video Graphics Standard (640 pixels by 480 lines of resolution on display)
Visible	Light with wavelengths in the range 380 – 750 nm
WAVE	Wrist Attached Video Equipment (L-3 DS acronym for wrist display system)
WiFi	Nickname for IEEE 801.11x (x=a,b,g,n,y) wireless data transmission standard
Win CE	Microsoft Windows Compact Edition (operating system for handheld devices) used on Spiral 4 WAVE

APPENDIX A.
INTELLECTUAL PROPERTY RESULTING FROM THIS PROGRAM

L-3 DS has patent applications in process for work done using company-funded IRAD and cost-sharing funds with respect to various aspects of the wearable wrist display development. These are:

Title: Wrist Attached Display System for Unmanned Vehicle Imagery and Communication
Inventors: Robert C. Anderson, Jerome S. Conway, Dave C. Huffman, and Keith I Tognoni
Assignee: L-3 Communications Corporation
U.S. Patent Application Number: 11 / 072,104 filed March 4, 2005,
Notice of Publication issued September 7, 2006.

Title: Wearable Electronic Device with Edge-Mounted Battery
Inventors: Robert C. Anderson and James Pierce
Assignee: L-3 Communications Corporation
U.S. Patent Application Number: 60 / 807,871 filed July 20, 2006

Title: Electronic Device to be Worn on the Arm
Inventors: Robert C. Anderson and James Pierce
Assignee: L-3 Communications Corporation
U.S. Patent Application Number: 29 / 247,928 filed July 20, 2006
D572,266

Title: Wrist Pouch for Electronic Equipment
Inventors: Robert C. Anderson and James Pierce
Assignee: L-3 Communications Corporation
U.S. Patent Application Number: 60 / 807,884 filed July 20, 2006

Title: Wearable Communication Device with Contoured Back
Inventors: Robert C .Anderson
Assignee: L-3 Communications Corporation
U.S. Patent Application Number: 11 / 608,875 filed December 11, 2006

Title: Wrist Pouch for Electronic Equipment
Inventors: Robert C. Anderson and James Pierce
Assignee: L-3 Communications Corporation
U.S. Patent Application Number: 11 / 668,119 filed January 29, 2007

APPENDIX B.
PUBLICATIONS, PRESENTATIONS, AND DEMONSTRATIONS

B1. Publications

1. David C. Huffman, “Applications of advanced display technology for dismounted combatants (Invited Paper),” in *Cockpit and Future Displays for Defense and Security*, ed. by Darrel G. Hopper, Eric W. Forsythe, David C. Morton, Charles E. Bradford, Henry J. Girolamo, Proceedings of SPIE Vol. 5801, pages 59-63 (SPIE, Bellingham, WA, 2005).

B2. Presentations

1. “Applications of advanced display technology for dismounted combatants”, by Dave Huffman, (Invited Paper), SPIE Cockpit Displays Conference, Orlando FL, 30 March 2005.
2. “Advances in mobile displays for enhanced situational awareness,” by David Huffman, Society for Information Display (SID) Americas Display Engineering and Applications Conference (ADEAC), Atlanta GA, 24 October 2006.

B3. Demonstrations

1. Demonstration to Mike Willis, Head, Avionics Development Branch, Electronics Systems Laboratory, Georgia Tech Research Institute, August 17, 2006 (private).
2. L-3 Communications Shareholders Meeting, New York City, April 2006 and April 2007 (demonstration with Rover)
3. Demonstration in booth at International Association of Chiefs of Police, Boston MA October 2007 (trade exhibition)
4. Demonstration to Army special projects group at Battle Command Battle Lab, Fort Huachuca AZ, August 2007 (private)

**APPENDIX C.
PROFESSIONAL PERSONNEL ASSOCIATED WITH THIS PROGRAM**

Persons who contributed to technical work on this effort by role are listed below.

Company	Name	Role in This Program
L-3 Display Systems, Alpharetta GA		System Integration for WAVE Spirals 3 & 4
	Mr. David Huffman	Technical Lead
	Mr. William Bates	Program Manager, Flexible Displays
	Ms. Linda Tarver	Program Manger, Wrist Displays
	Mr. Keith Tognoni	Lead Engineer, Electrical
	Mr. Robert Anderson	Lead Engineer, Mechanical Design
Slingshot Product Design Group, Duluth GA		Design and Fabrication of Spiral 3
	Mr. Sam Zaidspiner	President
	Mr. George Hatzillas	Lead Engineer
	Mr. Noah McNeely	Lead Designer
Anders Electronics, London, UK		Processor for WAVE Spiral 4
	Mr. Brent Singer	Program Manager
	Mr. Alex German	Electrical Engineer
Valigent, Ltd., Kfar Saba, Israel		Software for WAVE Spiral 4
	Mr. Mike Dvorkin	Hardware Engineer
	Mr. Lev Korsunsky	PCB Design Engineer
	Mr. Mike Heifets	Design Team Manager
Embedded Solutions, Ltd., Even Yehuda, Israel		Software for WAVE Spiral 4
	Mr. David Ohayon	Software Engineer
	Mr. Abraham Kcholi	Software Engineer