Preserving a Legacy

Integration of SAASM and Commercial GPS Receivers with Existing Shipboard Systems

With the GPS portion of consumer products' bill of materials no more than a few dollars, some people might come to think of positioning, navigation, and time (PNT) as a disposable item — a feature that they'll pick up again with their next cell phone. But in the military realm — and also in many commercial applications — where installation costs and standards-based form, fit, and function requirements dominate the operational and financial considerations of GPS equipage, things aren't quite so simple. Many platforms — ships, aircraft, land vehicles — need to have their PNT capabilities upgraded while preserving the onboard legacy systems. Not a trivial matter, as we see from this engineering case study involving replacement of a venerable shipboard navigation system.

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URSA NAVIGATION SOLUTIONS

The U.S. Navy's Ship Transfer program helps satisfy U.S. foreign policy objectives and the defense requirements of allied and friendly nations by fostering interoperability among military vessels and on-board systems, which helps strengthen mutual defense arrangements among these nations.

Under the Foreign Military Sales (FMS) Program the United States offers retired U.S. Navy and U.S. Coast Guard vessels to these nations' military services. Export controls require that the vessels be sanitized of classified and sensitive material prior to the transfer.

The AN/WRN-6 (WRN-6, for short) Satellite Signals Navigation Set is a militarized GPS navigation system used on many U.S. Navy combatant ships and submarines to provide precise and accurate geographical position information to the ship's navigation and combat system. The WRN-6 can track up to five satellites and receive and process the L1 and L2 P/(Y) code and L1 C/A code. The navigation system is also capable of Selective Availability and antispoofing (SA/AS) operation.

However, vessels carrying the WRN-6 set may not be released to certain countries, effectively breaking the integration between the navigation and combat sys-

Greek mine hunter at the Gulf Copper Shipyard

tems. A missing WRN-6 stops the flow of geographical information among the ship's systems, compromising the safe navigation and the fighting capability of the ship.

Moreover, the WRN-6 incorporates an aging GPS receiver that was first designed, built, and installed on vessels beginning in the 1980s. Consequently, it has long been targeted for replacement with upgraded technology. On February 24. 1999, Vice Admiral James F. Amerault, Deputy Chief of Naval Operations (Logistics) addressed the Armed Forces House Subcommittee stating that "The WRN-6, installed in most of our ships, has no growth potential, latent defects, and does not support Navigation Warfare or electronic charting."

The AN/WRN-7, an unclassified replacement for the WRN-6, has been installed in a limited number of FMS ships. The WRN-7 is identical to the WRN-6 with the exception of KYK input for loading P/Y-code encryption keys. It is vulnerable to the same latent defects as the WRN-6.

To maintain full operational readiness of navigation and combat systems for FMS fleets, the U.S. Navy required a functional, exportable replacement to be developed for the WRN-6 and WRN-7. This system needed to use existing shipboard cabling, mount to existing shipboard mounts, offer the same interfaces, and work across all FMS platforms. It also had to support being outfitted with either a commercial or a military GPS receiver, depending on the platform.

This article describes the development of such a WRN-6/WRN-7 replacement system by our company.

Technical Standards Challenges

Unfortunately, the WRN-6 shown in the accompanying photo is not like a typical commercial GPS receiver. It consists of an R-2331/URN radio receiver, an AM-7314/URN antenna amplifier, an AS-3819/SRN or AS-3822/URN antenna, and a C-11702/UR indicator control.

The radio receiver features a unique U.S. Navy input/output suite. It supplies data to the navigation or combat systems via the dual MIL-STD-1397 Naval Tactical Data System (NTDS) Type A or Type B interfaces. (See the accompanying sidebar, "Standards and ICDs," for a list of the military standards and interface control documents or ICDs used by the WRN-6/7 and its replacement.)

In addition to the dual Navy Tactical Data Systems (NTDS) interfaces, the radio receiver also contains a synchro interface for roll, pitch, heading, and speed input; a DOD-STD-1399, Section 441, Precise Time and Time Interval (PTTI) interface; an ICD-GPS-060 HAVEQUICK interface; and an ICD-GPS-150 instrumentation port data link interface.

The PTTI interface has a 1 pulse per second (PPS) input, 1 PPS output, and a 1 pulse per minute (PPM) output. The unique interfaces found on the WRN-6 means that no commercial alternatives are available to replace it.

Some other U.S. Navy systems, such as the Navigation Systems Sensor Interface (NAVSSI) and the Enhanced Control Display Unit (ECDU), could possibly be integrated into the FMS fleet. However, these systems are based on a VERSA Module Eurocard (VME) chassis and are physically much larger than the WRN-6. Integrating one of these systems would be expensive and time consuming.

These systems feature the GPS VME Receiver Card (GVRC) as the sole sensor providing GPS data. The GVRC provides the Precise Positioning Service (PPS) used by NAVSSI and the ECDU to provide time and navigation data to U. S. Navy shipboard users. Like the WRN-6, the GVRC has become obso-

(top) WRN-6 radio receiver
(bottom) Indicator control

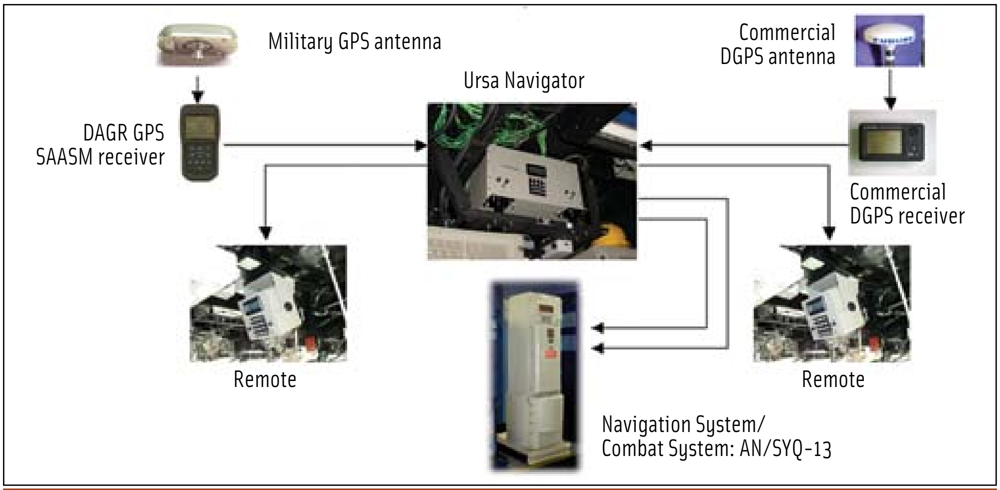

FIGURE 1 Ursa Navigator functional diagram

Ursa Navigator and remote

lete and does not meet some of the newer requirements for a GPS provider, such as the requirement for Selective Availability Anti-Spoofing Module (SAASM) compliance.

However, the Defense Advanced GPS Receiver (DAGR) and the U.S. Army Standard Embedded Receiver, Ground based GPS Receiver Application Module (Gb-GRAM) both feature the Nighthawk 12-channel GPS signal processor and have the next-generation SAASM capabilities.

Our Approach

We studied the problem and arrived at a low-cost, practical solution that was implemented into a commercial product in 2007. This involved the design, development, and manufacture of an interface between an NMEA-capable GPS receiver — either commercial or military, for example, the Defense Advanced GPS Receiver (DAGR) — and the navigation and combat systems that implement the WRN-6 protocols.

This approach ensured that navigation and combat systems would receive the information they required in the format they expected, to the limits of the accuracy available in the GPS signals. As an unclassified, commercial product, our Ursa Navigator is logistically supportable for the foreseeable future, is flexible and easily integrated into a variety of different platforms, and also conforms to export control requirements.

The Ursa Navigator and its remote are based on an industry standard architecture supported by multiple vendors and GPS receiver technology. Our engineers have designed a system that emulates the basic functionality of the WRN-6 and its control indicators while supporting dual NTDS A or B channels. Figure 1 presents a functional diagram of the Ursa Navigator.

The Ursa Navigator bolts to existing shipboard mounts, accepts two GPS NMEA-0183 inputs, provides a battery back-up, features menu-driven operation, includes built-in test, and has hardware connectivity for future upgrades such as NMEA 2000, 100BASE-TX, or 100BASE-FX.

Depending upon the selected GPS unit, enhanced positioning can be achieved through differential capability, such as that provided by the Nationwide Differential Global Positioning System (DGPS), the Federal Aviation Administration's Wide Area Augmentation System (WAAS), the European Geostationary Navigation Overlay Service (EGNOS), or Japan's Multi-functional Transport Satellite (MTSAT), For qualified end-users, enhanced positioning using a militarized GPS receiver such as the DAGR is also available.

The Ursa Navigator accepts NMEA 0183 input, rendering the data into the proper NTDS format. Our solution requires no changes to any aspect of existing shipboard systems. As part of "original" outfitting, the Ursa Navigator is a drop-in replacement for the WRN-6. The Ursa Navigator can also operate as a backup for existing WRN-6 equipment.

A failed WRN-6 can quickly be removed and replaced with the Ursa Navigator plus an NMEA-compliant

Standards and ICDs

1. MIL-STD-1397 — Military Standard - Input/Output Interfaces, Standard Digital Data, Navy Systems
2. DOD-STD-1399 — Military Standard – Interface Standard for Shipboard Systems, Section 441, Precise Time and Time Interval (PTTI)
3. ICD-GPS-060 — GPS User Equipment – Precise Time and Time Interval (PTTI) Interface
4. ICD-GPS-150 — GPS User Equipment - Interface Control Document for Instrumentation Port Data Link of the DoD Standard GPS UE Radio Receivers
5. MIL-S-901D — Military Specification – Shock Tests, H.I. (High-Impact) Shipboard Machinery, Equipment, and Systems, Requirements for
6. MIL-STD-461E — Military Standard – Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment
7. MIL-STD-1399 — Military Standard – Interface Standard for Shipboard Systems, Section 300A, Electric Power, Alternating Current

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(left) SRC-40 mounted to the lightweight shock machine
(above) Front panel of the SRC-40 as the hammer strikes the anvil

GPS receiver. Additionally, in cases where the platform never included a WRN-6, the Ursa Navigator provides a GPS input into the combat and navigation systems.

The chassis of every Ursa Navigator has the mounts for an internal GPS receiver. The battery charger circuit card that handles power distribution has an electrical receptacle for an internal GPS power connector. The Navigator was designed to accept the U.S. Army standard embedded receiver, a Ground-Based GPS Receiver Application Module (Gb-GRAM); however, a commercial GPS receiver could be installed in the same location.

Customers can order a Ursa Navigator with the internal GPS option. All GPS receivers with selective availability/antispoofing modules (SAASMs) would have to be supplied by the customer.

Designing for the Shipboard Environment

Integrating commercial equipment with a U.S. Navy shipboard navigation or combat system presents some unique challenges. The shipboard environment can be harsh and imposes many stresses on the equipment not faced by most commercial or consumer products.

We needed to address shock, electromagnetic interference (EMI), power, and temperature factors during the initial design phase. To minimize the development time and costs, we chose to incorporate proven engineering approaches from qualified designs and use identical components wherever possible. This duplication of technology enabled us to ensure the survivability of the replacement system without implementing the actual tests.

In the area of shock, we borrowed many of the engineering approaches that we employed in the development of a shipboard UHF transmitter, the AN/SRC-40. The transmitter was tested on the lightweight shock machine to MIL-S-901D, as seen in the accompanying photo.

During MIL-S-901D testing the equipment is subject to nine blows — three blows on each axis. A 400-pound hammer is dropped from one-, three-, and five-foot heights. Accompanying photos show the AN/SRC-40 just before and as the hammer strikes the anvil bearing the unit.

In this process, the AN/SRC-40 serves as a kind of surrogate. The Ursa Navigator itself was not subjected to shock testing, which is very expensive. Such tests have not been a requirement for any of the FMS platforms. If we were to put the Ursa Navigator on a U.S.Navy ship with MIL-STD-901D, shock testing would be required.

Testing like this quickly identifies which engineering approaches can withstand shipboard shock requirements and which can't. The Ursa Navigator shares many of the front panel components found on the SRC-40. We used these components and their mounting techniques as well as, wherever possible, circuit boards interconnected using a header and receptacle similar to those implemented by the PC/104 specifica-

The Ursa Navigator mounted onboard an MHC ship

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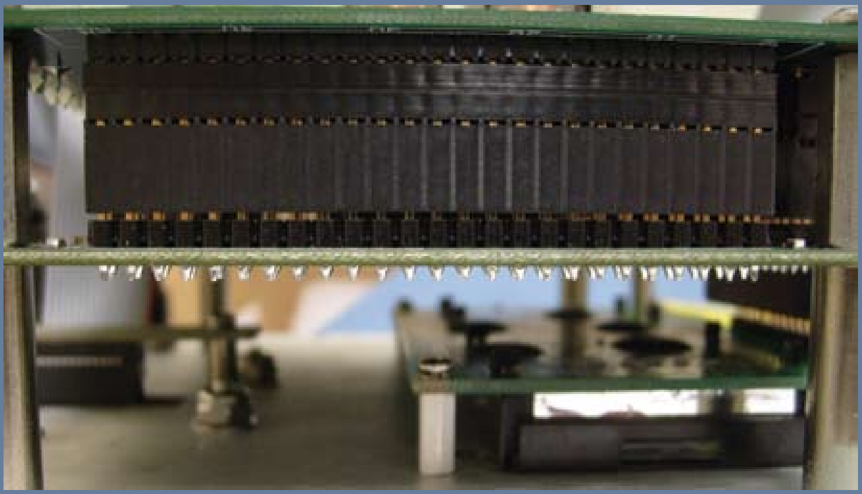

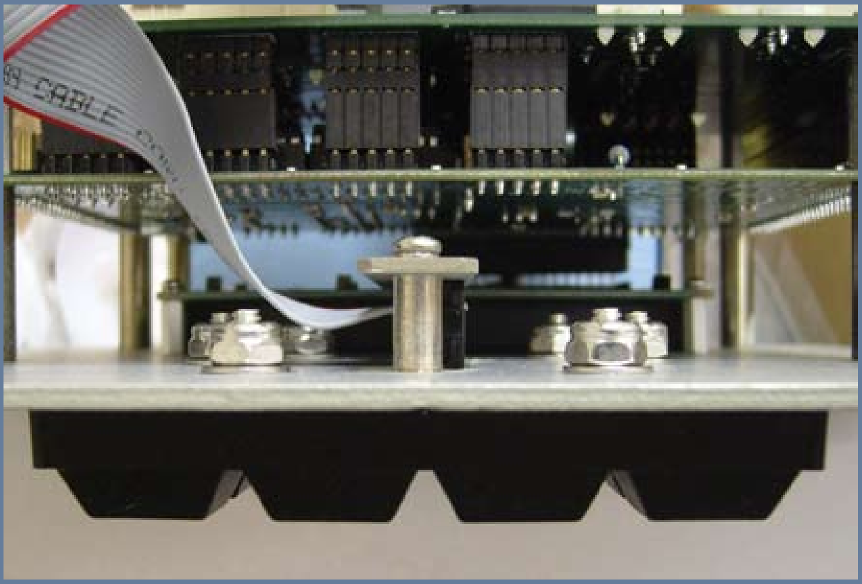

(top)Circuit board interconnections that minimize the use of wires and cables (middle)Keyboard mounted to the front panel with ribbon cable retainer (left) Close up of ribbon cable retainer

tion. This type of interconnection technique improves reliability, survivability, and minimizes wiring and cables.

To reduce component costs and assembly time, ribbon cables and connectors were employed wherever possible. We used metal retainers to hold the ribbon cable connector in place when conventional latches could not be used. The low mass of the ribbon cable assembly and the strength of the metal retainer allow these interconnections to survive high-g forces generated during shock testing.

MIL-STD-461E provides detailed testing requirements for the control of electromagnetic interference characteristics of subsystems and equipment. During the design of the Ursa Navigator, we focused on radiated emissions, radiated susceptibility, conducted emissions, and conducted susceptibility.

Electromagnetic interference (EMI) is a two-way street. A design has to take into account the effects of external interference as well as those the equipment can have on other equipment. MIL-STD-461E focuses on four areas; conducted susceptibility, radiated susceptibility, conducted emissions, and radiated emissions.

EMI can interfere with a GPS receiver in several different ways. Noise on the power line (conducted emissions) to the GPS receiver can interfere with receiver operation. This can occur whether the receiver is mounted internally or externally. Noise in the air (radiated emissions) can also interfere with the operation of the GPS receiver.

The Ursa Navigator uses an aggressive AC power line filter to attenuate power line noise, which is electrical energy with a frequency higher than the fundamental frequency of the power line. Noise is best described as any unwanted electrical signal.

This filter attenuates unwanted electrical signals from the Ursa Navigator's electronics so that they are not present on the power line being shared by other electronic equipment. It also prevents unwanted electrical signals from entering the Ursa Navigator and interfering with the proper operation of the electronics and the GPS receiver.

AC power is only half of the problem. The Ursa Navigator has an internal DC bus that receives power from an AC to DC power supply or a battery upon loss of AC power. The GPS receiver operates on a DC voltage.

Filtering must be present on the DC supply to the GPS receiver and other electronics inside the Ursa Navigator. This filtering attenuates unwanted electrical signals for both internal and externally mounted GPS receivers.

Radiated emissions and radiated susceptibility are handled with shielding and grounding. Sometimes several layers of shielding are required to ensure proper operation of the GPS receiver. The Ursa Navigator's metal enclosure is the first line of defense from radiated interference from an outside source. The conductive enclosure forms a Faraday cage that blocks electrical signals from entering or exiting the enclosure.

To take full advantage of the Faraday cage the Ursa Navigator's enclosure is also grounded with a heavy gauge copper conductor to the ship's grounding bus. Mine hunting ships are designed to be as non-magnetic as possible; so, the Navigator is not grounded to the ship's bulkhead as it might be on a frigate or destroyer.

The Ursa Navigator has many receptacles that are electrically bonded to the rear panel of the Navigator with an EMI gasket. This bond extends the Faraday cage to the connector and shielded cable that mate with the receptacle.

If a GPS receiver is mounted internally in the Ursa Navigator, two additional shields are typically required. The manufacturer places one shield over the GPS receiver. We place another shield over the GPS receiver assembly and supporting electronics. This double shielding ensures proper GPS receiver operation in an EMI rich environment.


Receptacle with EMI gasket

In implementing these measures we again borrowed proven technology from qualified designs.

We addressed radiated emissions and susceptibility with military qualified receptacles and EMI gaskets as shown in the accompanying photo. Each receptacle has a conductive EMI gasket sandwiched between the receptacle and the rear panel.

The inside of the rear panel is not powder-coated to minimize resistance and allow a good electrical bond between the receptacle, gasket, and rear panel. The silicone that forms the gasket also seals the receptacle to the rear panel preventing liquids from entering the unit.

To reduce conducted emissions and the susceptibility of system operation from conducted emissions, we used a high performance power line filter shown in the photo below. This filter was developed specifically for switching power supplies and is designed to control conducted emissions all the way down to 10 kHz. This filter also meets the line-to-ground capacitance requirements of MIL-STD-1399.

When it comes to electrical power, the shipboard environment can be challenging for the design engineer. Whenever a ship pulls in or out of port, power is transferred between shore power and ship's. Power transfers may also occur when equipment is shifted from one bus to another. These transitions can cause a brief loss of electrical power, voltage sags, or voltage spikes.

Power transfers can wreak havoc on an unprotected GPS receiver. A brief loss of power or a voltage sag can shut the receiver down. A voltage spike can permanently damage the receiver in the same way that a lighting strike at home can destroy an unprotected computer.

There are several ways to prevent these events from interrupting system operation. One is to electrically isolate the equipment during the transition from shore power to ship power or shifting from one bus to another. This can be accomplished simply by opening the circuit breaker to the equipment. However, securing power to the equipment typically turns the equipment off.

The Ursa Navigator features a built in battery back-up that maintains full operation of the main unit, remotes, and GPS receivers during the loss of power. The operator can secure AC power to the Ursa Navigator during transfers preventing it from experiencing any voltage transients. After the transfer is complete the operator simply turns AC power back on. The battery pack will also maintain full operation of the Ursa Navigator, remotes, and GPS receivers for up to 45-minutes during the loss of power.

Not all power problems can be predicted as easily as a shift from shore to ship power. From time to time, all shipboard equipment will experience some type of power disturbance. Although the battery backup maintains the Ursa Navigator, remotes, and GPS receivers during a loss of power, it does not offer protection from voltage spikes.

Such spikes are typically attenuated by metal-oxide varistors (MOVs). Virtually every power strip on the market offering some type of surge suppression uses one or more MOV. We employed this same technology in the Ursa Navigator.

However, we did not choose MOVs typically found in a surge suppressor. Instead, we selected a heavy-duty

Power line filter

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industrial MOV, pictured here, that is designed to provide surge protection for motor controls and power supplies used in oil drilling, mining, and transportation equipment. These MOVs can survive peak currents of up to 40,000 amps.

Unlike an office environment, the shipboard environment may not always have air conditioning. Consequently, we sought to design a product that could operate in ambient conditions of up to 50° C while not exposing any of its internal components to the outside air. This offered many advantages: it eliminated the need for filters and kept dust off of the components, thus permitting consistent thermal conductivity while reducing corrosion and enhancing EMI characteristics. This approach also reduces maintenance and ambient noise levels.

Heavy-duty industrial metal-oxide varistors

During the proof-of-concept stage, we used multiple thermistors to monitor temperatures inside and outside of the cabinet. In the final design, we also incorporated thermistors to monitor internal air temperature and battery temperature. The temperature data is made available to the operator on the front panel of the Ursa Navigator or the remotes.

Test Procedures

Testing is a very important step in the manufacturing process. It allows us to evaluate the performance and reliability of the equipment prior to shipping. So, we test each system extensively before installing it on a ship.

Initially, each system is tested in our in-house lab for a period of a week or more. We monitor the performance of each system with a computer.

UrsaNav developed the software used to test each Ursa Navigator. It is based on Interface Design Specification (IDS) NAVSEA SE 174-AB-IDS-010/GPS. The software simulates the device with which a WRN-6 would interface such as the AN/SYQ-13 console, AN/UYK-7 computer, or an AN/WSN-5 inertial navigation system (INS).

The IDS is an NTDS interface; the computer used for testing is outfitted with NTDS interface cards. The Ursa Navigator and the computer are interconnected with shipboard type NTDS cables.

The testing software allows a comparison of the GPS data input to the Ursa Navigator and the data transmitted over the NTDS interface. The NTDS transmission between the Ursa Navigator and the other device is bidirectional.

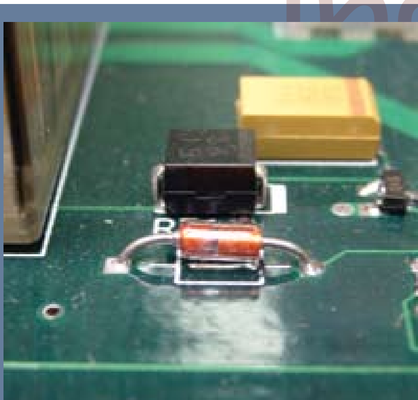
A device such as the AN/WSN-5 will transmit data including position and velocities to the Ursa Navigator. The Ursa Navigator or the remote can display this data. With the testing software, we can simulate any data that the AN/WSN-5 can send to the Navigator.

After any problems are detected and corrected, we subject the unit to a new testing cycle. Only after the unit has completed this testing cycle is it considered ready for installation onboard a ship.

Onboard Installation

Installing equipment onboard a ship can present some unique challenges. No two ships are created exactly alike. So, we always need to conduct a pre-installation ship check.

This step provides the installation crew with an opportunity to examine the ship against any available engineering drawings, which can be updated as necessary and photographs taken to supplement the information gathering. By the end of the ship check, the installation crew should know what to bring on the installation and how long the installation will take.



(above) Thermistor mounted on a circuit board
(right) Display showing environmental data

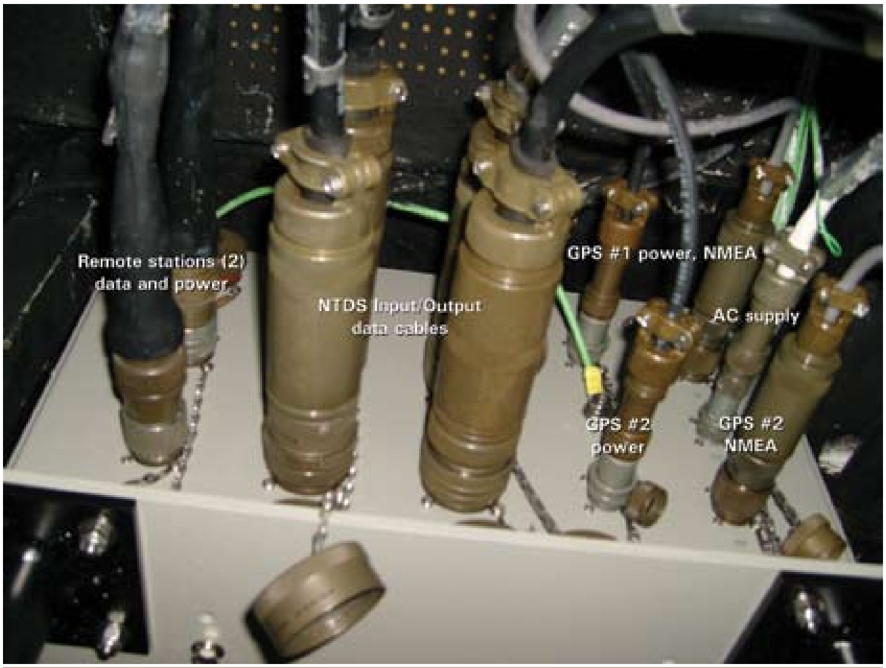


FIGURE 2 Rear panel of the Ursa Navigator with shipboard cables connected. Six cables are required for GPS data distribution. Two small cables, one for each external GPS receiver, and four large cables required for the NTDS interface.

The ship check is also a time for the installation crew to establish a relationship with the ship's crew to build confidence in the new equipment and the installers, without which a successful installation may not take place. The relationship between the installation crew and the ship's crew extends throughout and preferably after the installation process.

Prior to the installation, the installation crew certifies the proper operation of existing shipboard systems and cabling. Not performing this step can greatly increase troubleshooting time should a problem arise with the installation.

To minimize installation time and reduce installation costs, the Ursa Navigator and remote were designed to bolt right into the old WRN-6 and control indicator mounts. The receptacles on the back of the Ursa Navigator and remote are in the same physical location at those on the WRN-6 and control indicator. This allows the existing cables to be connected without modifications.

As can be seen in **Figure 2** depicting the rear panel of the Ursa Navigator, the existing shipboard cables and connectors are not small nor do they lend themselves well to being repositioned.

The Ursa Navigator and remote are both supplied with mounts that are drilled on shipboard location. This allows the installer to place the equipment in the optimal location before bolting it down. It also compensates for variations in the mounting hardware used for the legacy systems and allows existing bolt holes to be used. Notice in the accompanying photo of the Ursa Navigator mounted in the old WRN-6 location that no new bolt holes were drilled. Because the remote is physically smaller than the legacy control indicator, mounting holes are drilled into the legacy mounting plate.

The Ursa Navigator typically interfaces with two GPS receivers: GPS/WAAS/DGPS receiver and a DAGR. The GPS receiver is mounted on the bridge and shown in the accompanying photo. The DAGR had not been provided at the time of installation of the Ursa Navigator.

The ship operator can select the GPS used for navigation or can select an auto mode that allows the Navigator to select the best-performing GPS unit at the time. If a problem arises with one receiver, the system will automatically switch to the other. This is a feature that U.S. Navy ships with the WRN-6 do not have. The Greek Navy just needs to plug the DAGR into the cabling.

Training

Installing a new piece of equipment onboard a vessel always requires training of the ship's crew.

For the Ursa Navigator, the installation crew is also the training crew. Our lead technician serves as a subject matter expert on the operation and maintenance of the equipment, spending whatever time is needed to fully instruct the ship's crew. This is another reason why the relationship between the installation crew and ship's crew is so important.

Fleet Operations

We performed the first Ursa Navigator installation in September 2007 on board two Greek mine hunter vessels: the HN Kalypso and HN Evniki, formerly known as the USS Heron (MHC-52) and USS Pelican (MHC-53). The installation took place while the ships were in Texas at the Gulf Copper Shipyard.

After installation activities in the shipyard, the vessels returned to Greece where they now employ the Ursa Naviga-

(top) Bottom view of the Ursa Navigator mounted in the old WRN-6 location (bottom)Remote installed to the old control indicator mount

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A WAAS/DGPS-capable receiver mounted in the bridge

tor on a regular basis. According to our customer, the Ursa Navigators have been problem-free since they were installed on the Greek ships seven months ago.

The next installation, scheduled for May 2008, will be onboard two Egyptian mine hunters — the al Shareen and al Faroq, formerly known as the USS Cardinal (MHC-60) and USS Raven (MHC-61). An Ursa Navigation Solutions crew will perform the installation in Egypt at the Egyptian Navy shipyard located in Ras-El-Tin, Alexandria. After the installation, sea trials will again be performed to test operation of the Ursa Navigator.

Support and Service

It is impossible to design a perfect piece of equipment, something that never breaks. All equipment will have problems and solving those problems will require spare parts. The Ursa Navigator and remote were engineered so that replacement parts will be available years from now. They also feature interchangeable parts. All of the circuit boards used in the remote are also used in the Ursa Navigator itself.

The single-board computer and interface board in the remote can be placed in the Ursa Navigator; only a jumper setting needs to be changed to make the transition successful. Interchangeable parts between the Ursa Navigator and remote reduce the number of spare parts that the ship needs to carry, simplifying logistics.

Integrating New Technology into Other Areas

To build upon the success of the Ursa Navigator, we began looking at other pieces of legacy shipboard navigation equipment that needed a technology upgrade. We turned our attention to the AN/WSN-2 and the AN/WSN-5. The AN/WSN-2 (WSN-2) is a stabilized gyrocompass set that provides precision, analog, dual-speed roll, pitch, and heading signals for use by the ship's equipment. The AN/WSN-5 (WSN-5) is an inertial navigation system that provides the same outputs as the WSN-2 plus position data.

Both the WSN-2 and the WSN-5 feature "iron gyro" technology, which has been replaced with ring laser gyro (RLG) technology on virtually every U.S. Navy ship. RLGs represent a major improvement over the older technology and are available in various form factors.

An inertial measurement unit (IMU) could contain a monolithic RLG consisting of a single three-axis cube or three single-axis RLGs. We chose to develop a replacement for the WSN-2 and the WSN-5 based on a monolithic ring laser gyro.

These bolt-in replacements, called the Sea Compass and Sea Navigator, feature the same footprint and connectivity, including compatible synchro outputs, as the WSN-2 and WSN-5. However, they offer significantly improved performance, require no maintenance, and are very cost-effective.

The Sea Compass does not interface with a GPS. It is simply a gyrocompass; so, no GPS fix is required. The Sea Navigator has many GPS options. The receiver can be either internal or external. Optional external interfaces include NMEA, ICD-GPS-150, or NTDS NAVSEA SE 174-AB-IDS-010/GPS.

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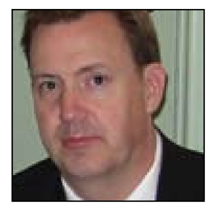
Manufacturers

The WRN-6 was manufactured by **Rockwell Collins**, Cedar Rapids, Iowa, USA. The WAAS/DGPS-capable receiver is a GP-37 from **Furuno Electric Company, Ltd.**, Tokyo, Japan. The WSN-2, WSN-5, and WSN-7 are manufactured by **Sperry Marine**, Charlottesville, Virginia, USA. Our test procedures included use of a LA1034 LogicPort from **Intronix Test Instruments, Inc.**, Phoenix, Arizona, USA; a 199C Oscilloscope from **Fluke Corporation**, Everett, Washington, USA; and an SL206 AC/DC current probe from **AEMC Instruments**, Foxborough, Massachusetts, USA.

Authors



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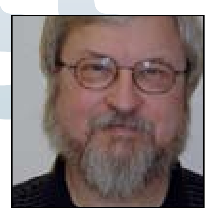

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