# Hull Fairness and Accuracy Control
# Phase II Final Report

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# 1. Introduction

## 1.1 Purpose/Problem Statement

The purpose of this report is to compile and summarize Phase II activities as accomplished via the Hull Fairness & Accuracy Control (HF & AC) Project with contractual period of performance (POP) 04 December 2007 through 31 December 2009 and carried out by Northrop Grumman Shipbuilding, Gulf Coast Operations (NGSB-GC). Please note that a summary of Phase I activities (having occurred January – December 2008) can be found in previous deliverables 6.0 and 7.0, Hull Fairness and Accuracy Control Inter-Sector & Market Technology Report; and Hull Fairness and Accuracy Control Phase I Final Report, respectively. This report will include but not limited to the inclusion of highlights from the following project activities: vendor training, site visits, vendor demonstrations, conferences and trades shows, technology transfer opportunities, and implementation plans of the project as a whole. Additionally, a set of procurement specs will be outlined for potential purchase of equipment.

## 1.2 Background

The United States Navy has continually increased requirements on its surface combatant vessels. This emphasis continues to be a driving factor and requirement parameter to be incorporated into new ship designs by the Navy and thus increasing various tolerances. The shipyards building these ships will be held to new requirements and higher manufacturing tolerances than have previously been used. The challenge is to couple the latest manufacturing techniques with the latest measurement technology and ensure that the requirements can be attained. Phase I activities attempted to identify best practices coupled with the latest metrology equipment and how to implement the findings into the manufacturing process in order to meet an increased requirement. Phase II activities include the lease of equipment as identified in Phase I for the purpose of field testing in a shipyard environment. These field testing periods allow for the shipyard to evaluate the utility of each piece of equipment and its viability as a cost savings and process improving catalyst.

## 1.3 Objectives and Approach

This project approaches the challenge of meeting a new and more stringent requirement by first finding a baseline of current capabilities and requirements. The baseline allows for capturing where the shipyard currently stands in terms of technology and processes as related to current requirements. It then allows for a systematic comparison to state of the art technology, other industry's processes, and ultimately the path forward as needed to meet the next generation surface combatant requirements. The baseline data is documented, in part, by a Gap Analysis provided as the project's first deliverable and includes additional information such as the identification of training gaps.

### 1.4 Assumptions

NGSB-GC originally focused the implementation of this project solely on the next generation surface combatant. As the project and acquisition strategy evolved over the past two years, implementation has expanded to include various applications. Additionally, the technology investigated therein and subsequent lessons learned from field testing periods have been discussed and shared with Bath Iron Works via teleconferences, face to face meetings, and quarterly reviews. Implementation of said technology may or may not be conducive for Bath Iron Works' (BIW) manufacturing environment. The results of the project and subsequent implementation as originally intended for the next generation surface combatant at BIW are contingent upon the buy in, acceptance, and management approval.

## 2. Vendor User Group Meeting

### 2.1 Geodetic Systems, Inc.: Melbourne, FL

Geodetic Systems, Inc. (GSI) holds a biennial user's group meeting near their headquarter offices in Melbourne, FL. The 2009 meeting was held at a local hotel on January 21-23. Northrop Grumman Shipbuilding – Gulf Coast was offered an invitation to this event at no charge, aside from travel expenses and time charged, as a result of owning a single camera photogrammetry system. The meeting gave the project team a chance to see the multi camera and real time photogrammetry system in action prior to leasing for the field testing portion of the project. Additionally, it enabled the team to ask the vendor some pointed questions in regards to the application for this specific equipment. Demonstrations set up by the vendor as well as technical presentations of real world applications given by user's of the equipment across various industrial fields enabled the project team to fully understand the capability of the system and thus better utilize it for the field testing period.

# 3. Technology Transfer Opportunities

## 3.1 Ship Tech 2009: Biloxi, MS

Ship Tech 2009, Shipbuilding Affordability – Working Together to Transition Technology to the Fleet, conference was held 10-11 March in Biloxi, MS. As part of technology transfer opportunities both encouraged and required by the project, an abstract was submitted and accepted by the conference. An overview of the Hull Fairness & Accuracy Control Project was delivered as part of the agenda at Ship Tech 2009. The venue allowed for a broad and captive audience to become familiar with the details of the project's goals, achievements, and future plans.

## 3.2 Northrop Grumman Shipbuilding: Newport News, VA

On 14 – 16 April 2009, the author traveled to a NGSB shipyard located in Newport News, VA in order to view the Surphaser Laser Scanner in action. The author's point of contact at the facility was Tim Warren, who had been leading an effort for bringing Direct Dimensions, Inc. (DDI) into their facility as a subcontractor for providing survey data capture as well as analysis work for the purpose of distortion study on thin plate panels. The onsite observation began at the small panel line where Daniel Haga of direct dimensions, Inc. was waiting to scan with the Surphaser Model 25HSX, HSX600M1 which is manufactured by Basis Software, Inc. located in Redmond, WA. Daniel was waiting for Mickey Curtician and Chris Russell, both of NGSB-NN X068, to complete a Faro Laser Tracker XI survey of the panel edges and pucks on the panel used to tie the two (Tracker and Scanner) surveys together. This particular survey was of a flat panel approximately forty feet by forty feet with no structure attached and sitting on the small panel line. The Surphaser was used in two different setup locations on the panel itself to scan data. Those two location were (1) approximately 1/3 of the way across the panel and centered and (2) the opposite 1/3 of the panel and centered. These two setup locations allowed the Surphaser to capture and fill in data that is not collected in about a 6 foot diameter directly beneath where it is setup and provide nearly 100% coverage of the panel. There were a total of 8 pucks, 4 on each end of the panel, hot glued to the "plate blanket", several panels butt welded together. These 8 pucks were first measured by the tracker with a 1.5" SMR and then 1.5" tooling balls (which had been acid etched to remove the chrome and then spray painted with a medium dark gray primer) were placed in each puck for the Surphaser to measure. These easily identifiable locations would then enable the tracker data to be easily tied into the scanner data. This allowed the additional points captured by the tracker at the four corners and at locations spaced roughly a foot or so apart along the edges of the plate to easily be transformed into the scanner data. This edge data was surveyed with the tracker since the scanner struggles to capture data at the edge of the panel due to contrast issues.

Each scan took approximately 9 minutes to complete after a 30 second preview scan was accomplished. It was also noted that the Surphaser requires no warm-up time and has only a power cord, similar to that of a lap top computer, and one connection to a laptop via USB. The preview scan is done first so the software can zero in on the particular area of interest for data collection performed by the Surphaser. This preview is performed in lieu of a complete 360 degree scan which could include overhead structure and other ‘noise’ that would otherwise have to be taken out post process. Surphexpress is the name of the software that is provided with the Surphaser and it is used for data collection but has no real means for analyzing the data. Daniel showed the author some of the settings (i.e. point density, survey stats, status bar, etc.) and he also commented that DDI utilizes Polyworks software to accomplish most of their post process analysis. The question was asked about analysis in Spatial Analyzer (SA) but DDI does not use it at this time. Each scan captured millions of points and was approximately 366MB in file size. These panels had no structure or cutouts and were simply flat panels which had been welded together and made for a fairly straightforward survey. Also of note, the panels of primary interest during the observation were all ¼” or less.

A second survey was observed on a panel which was approximately 40’ X 30’ and, similarly to the first survey, a laser tracker once again captured the reference points and edge data. The laser tracker required two different setups this time since the far edges were out of the line of sight of the tracker due to the stiffeners and structure. The Surphaser then was setup in 4 locations on either side of the panel in order to achieve the line of sight required to get the desired coverage of the panel. Once a preview scan was completed, the scans took only approximately 4 minutes since the scanner did not have to make a complete rotation due to setup location.

On the final day of the trip, the author drove to the headquarters of the software company that created SA, a software tool utilized at both NGSB-GC and NGSB-NN. New River Kinematics (NRK) is located only a short drive from Newport News in Williamsburg, VA. An invitation had been offered by co-founder Joe Caulkins to meet and discuss the latest innovations of their product and show the author around the metrology lab. Mr. Caulkins demoed how SA interfaces with the Metris MV224 that NRK had set up in their metrology lab. The Metris is a large machine and requires a desk size cart for power supply and computer; however, it is widely recognized to be a very accurate machine and versatile in its measurements. It does not capture data like a laser scanner but is rather laser tracker like in data collection, only without targets. The MV224 can be driven to specific locations and "scan" in specific locations. Its scan time is, however, significantly longer than, for instance, the Surphaser due to the Metris scanning in about a 6" wide area along a linear path that the user defines. Prior to my departure, Mr. Caulkins also mentioned that the Sokkia Total Station model RCTS3 could measure in the same fashion as the Metris (no targets required and drive to specific location) with about a 1.3mm accuracy (as opposed to .5mm or less with Metris) and at a fraction of the price of the Metris.

### 3.3 Joint Man Tech Meeting Review: Columbus, OH

The ONR ManTech joint review meeting was held at the Edison Welding Institute / Navy Joining Center in Columbus, OH on 16 June 2009. An update of the project status was presented at this annual event as part of technology transition opportunity. This meeting also allowed opportunity to directly brief the stakeholder as well.

### 3.4 Coordinate Metrology Systems Conference: Louisville, KY

The annual Coordinate Metrology Systems Conference (CMSC) was held in Louisville, KY on 20-24 July 2009. This event is devoted to three dimensional metrology and as such an ideal place to learn from vendors and users of 3-D metrology equipment the latest innovations and uses for such equipment.

> CMSC draws visitors from diverse sectors of manufacturing and science laboratories, and continues to be the premier conference for measurement professionals. In a span of three days, more than 20 technical presentations were delivered by expert metrologists and scientists. A big hit at the conference was the introductory course on metrology systems capabilities covering four basic technologies: photogrammetry, laser tracking, laser radar, and structured white light. (from: Jones, 2009)

Additionally, this event allows for representatives from all Northrop Grumman sectors to meet at its annual Northrop Grumman Mechanical Measurement & Alignment Professionals (NG-MMAP) Community of Practice (CoP) meeting. This event allows for information sharing, lessons learned, and general networking opportunities among Northrop Grumman users of 3-D Metrology. The 2009 NG-MMAP event invited three vendors in for an intimate and pointed discussion of their product. The vendors included Direct Dimensions, Polyworks, New River Kinematics, and Verisurf. This cross section of service provider and software developer allowed a chance for Northrop Grumman to have dedicated time to hear from these vendors and ask specific questions relative to any concerns and requests they may have in regard to the product.

### 3.5 Society of Manufacturing Engineers Conference: "Aerospace Measurement, Inspection & Analysis": Baltimore, MD

The Society of Manufacturing Engineers (SME) conference was held 29 September through 1 October 2009 in Baltimore, MD. Upon being referred by a colleague for presenting an overview of the HF & AC project, the author obtained approval to present at the mostly aerospace focused event. This event also provided for a technology transfer opportunity to a broader base of industrial manufacturers and engineers other than strictly shipyard focused. The conference, through its technical presentations and exposition hall, also allowed for insight into processes and utility of measurement equipment used throughout the aerospace industry.

# 4. Project Gantt Chart

| | Indicators | Task Name | Duration | Start | Finish |
|---|---|---|---|---|---|
| 1 | | **Hull Fairness and Accuracy Control Project** | **414.4 days** | **Mon 1/7/08** | **Thu 12/31/09** |
| 2 | ✓ | **Phase 1** | **200 days** | **Mon 1/7/08** | **Fri 12/19/08** |
| 3 | ✓ | Program Management | 200 days | Mon 1/7/08 | Fri 12/19/08 |
| 4 | ✓ | **Task 1.1: Conduct Requirements and Capability Survey** | **20 days** | **Mon 1/7/08** | **Fri 2/8/08** |
| 9 | ✓ | **Task 1.2: Receive Expanded Training** | **27.8 days** | **Mon 3/3/08** | **Fri 4/18/08** |
| 12 | ✓ | Draft Technology Transition Plan | 0 days | Mon 3/3/08 | Mon 3/3/08 |
| 13 | ✓ | **Task 1.3: Conduct Inter-Sector and Market Research** | **134.8 days** | **Mon 4/21/08** | **Thu 12/11/08** |
| 14 | ✓ | Perform inter-sector research | 128.8 days | Mon 4/21/08 | Mon 12/1/08 |
| 15 | ✓ | Perform market research | 128.8 days | Mon 4/21/08 | Mon 12/1/08 |
| 16 | ✓ | Develop list of desired equipment | 103.8 days | Tue 6/3/08 | Mon 12/1/08 |
| 17 | ✓ | Inter-Sector & Market Technology Report | 0 days | Sun 11/30/08 | Sun 11/30/08 |
| 18 | ✓ | **Technology Transfer** | **30 days** | **Tue 10/21/08** | **Thu 12/11/08** |
| 19 | ✓ | National Defense Industrial Associtation's 11th Annual Systems Engineering Conferen | 3 days | Tue 10/21/08 | Fri 10/24/08 |
| 20 | ✓ | NSRP Ship Production Panel Meeting | 2 days | Tue 12/9/08 | Thu 12/11/08 |
| 21 | ✓ | **Reports** | **136.8 days** | **Tue 4/8/08** | **Thu 12/4/08** |
| 22 | ✓ | **Q1 Report** | **0.8 days** | **Tue 4/8/08** | **Thu 4/10/08** |
| 25 | ✓ | **Q2 Report** | **20 days** | **Wed 6/11/08** | **Tue 7/15/08** |
| 29 | ✓ | **Q3 Report** | **4.8 days** | **Tue 10/7/08** | **Wed 10/15/08** |
| 32 | ✓ | Phase 1 Final Report | 0 days | Thu 12/4/08 | Thu 12/4/08 |
| 33 | ✓ | Go/No-Go Decision | 0 days | Thu 12/11/08 | Thu 12/11/08 |
| 34 | | **Phase 2** | **206.4 days** | **Mon 1/5/09** | **Thu 12/31/09** |
| 35 | | Program Management | 195 days | Mon 1/5/09 | Thu 12/10/09 |
| 36 | ✓ | **Field Test Target System Prior to Purchase** | **195 days** | **Mon 1/5/09** | **Thu 12/10/09** |
| 37 | ✓ | Field Testing of 1st Selected System | 49.6 days | Mon 1/5/09 | Tue 3/31/09 |
| 38 | ✓ | Receive Vendor Training and Familiarization Period on 1st Selected System | 10 days | Mon 1/5/09 | Wed 1/21/09 |
| 39 | ✓ | Field Testing of 2nd Selected System | 49.6 days | Mon 4/6/09 | Tue 6/30/09 |
| 40 | ✓ | Receive Vendor Training and Familiarization Period on 2nd Selected System | 10 days | Wed 4/1/09 | Fri 4/17/09 |
| 41 | ✓ | Field Testing of 3rd Selected System | 48 days | Wed 7/1/09 | Fri 9/25/09 |
| 42 | ✓ | Receive Vendor Training and Familiarization Period on 3rd Selected System | 4 days | Mon 7/6/09 | Fri 7/10/09 |
| 43 | ✓ | Analyze results | 20 days | Mon 9/28/09 | Fri 10/30/09 |
| 44 | ✓ | Create procurement specs | 25 days | Wed 10/28/09 | Thu 12/10/09 |
| 45 | ✓ | **Technology Transfer** | **118.4 days** | **Tue 3/10/09** | **Thu 10/1/09** |
| 46 | ✓ | Ship Tech Conference | 1.6 days | Tue 3/10/09 | Wed 3/11/09 |
| 47 | ✓ | LIPT Review | 1 day | Tue 6/16/09 | Wed 6/17/09 |
| 48 | ✓ | Society of Manufacturing Engineers Conference | 3 days | Mon 9/28/09 | Thu 10/1/09 |
| 49 | ✓ | **Reports** | **148 days** | **Wed 4/15/09** | **Thu 12/31/09** |
| 50 | ✓ | Q4 Report | 0 days | Wed 4/15/09 | Wed 4/15/09 |
| 51 | ✓ | Q5 Report | 0 days | Wed 7/15/09 | Wed 7/15/09 |
| 52 | ✓ | Q6 Report | 0 days | Thu 10/15/09 | Thu 10/15/09 |
| 53 | ✓ | Final report & Implementation Plan | 0 days | Thu 12/31/09 | Thu 12/31/09 |
| 54 | | **Final Project review** | **20.6 days** | **Tue 11/3/09** | **Tue 12/8/09** |
| 55 | ✓ | Prepare Briefing Materials | 15 days | Tue 11/3/09 | Fri 11/27/09 |
| 56 | | Deliver Briefing | 0.8 days | Tue 12/8/09 | Tue 12/8/09 |

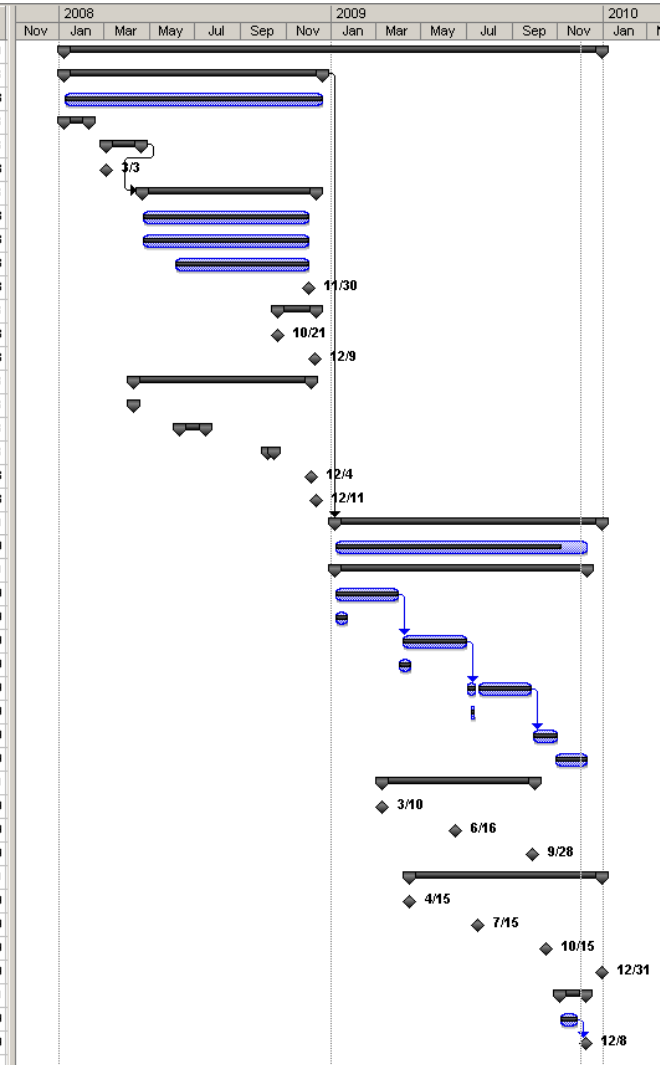


Figure 1. HF & AC Gantt Chart

# 5. Field Testing Periods

## 5.1 Automated Precision, Inc.: Laser Tracker 3

The Laser Tracker 3 from Automated Precision, Inc. (API) was the first down selected piece of equipment to be leased as part of the field testing period for the HF & AC project. The Laser Tracker 3 was received by NGSB-GC during the week of 05 January 2009. The first week was dedicated to onsite training provided with the lease. The training week included time with an engineer from the vendor who spent the week familiarizing NGSB-GC technicians with the equipment as well as giving ideas for applications. The main area of focus was within the panel line on targets of opportunity as they progressed through the panel line. The installation and alignment of several panel line automated welding machines was being scrutinized due to some alignment issues. The laser tracker measured the misalignment and as a result the out of alignment automated welding equipment was removed from the panel line. The equipment was shipped back to the manufacturer for repair and returned to the shipyard upon repair completion. The panel line has two of these particular automated welders and as a result of the findings on the first welder coupled with additional tests on the second welder, it too was repaired. Due to the extensive repair period of the automated welding equipment, manually welded stiffeners were measured for this field testing period for measuring distortion.

The panel line stiffener welding equipment was experiencing alignment and installation issues that the manufacturer of the equipment, Northrop Grumman, and Parson's (consulting and oversight provider for panel line installation) were aware of. However, the laser tracker was able to pinpoint definitive and quantifiable discrepancies with the equipment. For example, the weld head had approximately a 7/8" bow in it as it traversed across the panel line on its gantry, and the rails upon which it rode were not true. The ability to give real time data on the spot while all parties stood witness ultimately led to the disassembly of the stiffener welder and shipment back to the manufacture for redesign. The API Laser Tracker proved valuable in showing definitive results and expediting resolution where other methods / tools could not. In addition it proved its worth for future and periodic maintenance checks for alignment accuracies of equipment such as that in the panel line.

While the laser tracker was used primarily for measurements in the panel line, it was also used in other areas of the shipyard with a great deal of success. In addition to the previously mentioned installation and alignment of the panel line equipment the tracker was used very effectively in other areas. These areas include the following: foundation verification, pre cut unit integration, and combat system weapon alignment. The multiple applications in which the tracer can be effectively utilized along with its portability made it a favorite tool among technicians alike.

The API Laser Tracker 3 was used to take various measurements including monitoring the installation of stiffeners on the panel line. As described previously, the automated stiffener welder was inoperable due to unrelated installation and alignment issues. Nevertheless, measurements were gathered as manual welding processes were utilized in lieu of the automated machines. Discrete, predetermined points were measured and a sketch of a typical measurement setup is shown in Figure 2. The dotted lines are for reference and the solid lines represent the panel and stiffeners. Measurements were taken on the panel and indicated by the intersection of the dotted lines. These measurements were generally six inches on either side of the centerline of the stiffener and midway between the stiffeners at eighteen inch intervals. Additional shots were recorded by the technicians as they deemed necessary.

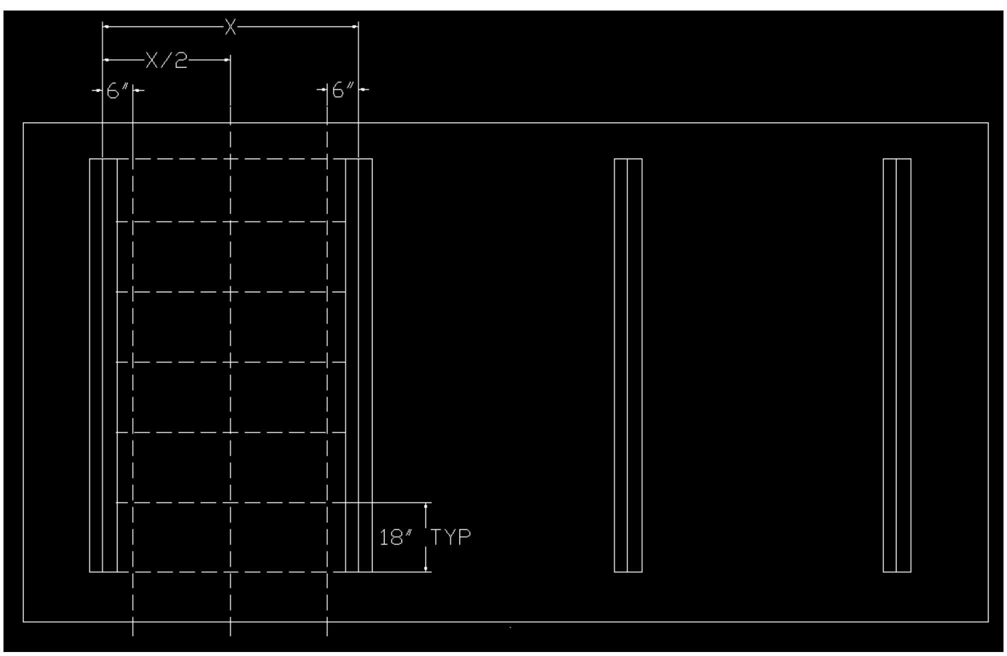


Figure 2. Typical Measurement sketch

Data collection was a balance between the amount of data that could be collected and the amount of down time incurred to production. Since production was generally required to be stopped while the data was collected, the technicians had to be prudent with their surveys. Data collected with the Laser Tracker requires a hard target, Spherically Mounted Retro reflector (SMR), to be placed at each data point. This process is depicted in Figure 3 and the SMR can be seen attached to the end of an extension pole. This extension was used so that distortion caused by the weight of the technician did not become a bias error. Measurements were taken multiple times at each data collection point; including a baseline (prior to weld), once each after the single sided track welder made a pass, and then a final after weld measurement. In process measurements were difficult to obtain for various reasons including the need for the hard targeting and the logistics of the single sided manual track welder, however, the surveys taken after each of the sides of the stiffener were taken can be considered in process in this instance. In process data was also difficult to obtain in some instances because of the radiant heat given off by the metal which caused the light of the laser to diffract hence giving erroneous data or no data at all. A typical half inch panel is shown in Figure 3 and a subset sample size of roughly twenty feet long by eight foot wide yielded results of approximately seven sixteenths distortion delta from baseline condition to final weld out condition. The resulting distortion results and associated deltas (represented by the point whiskers) are shown in Figure 4 in the software, Spatial Analyzer.

Figure 3. API Laser Tracker 3 Measurements on Panel Line

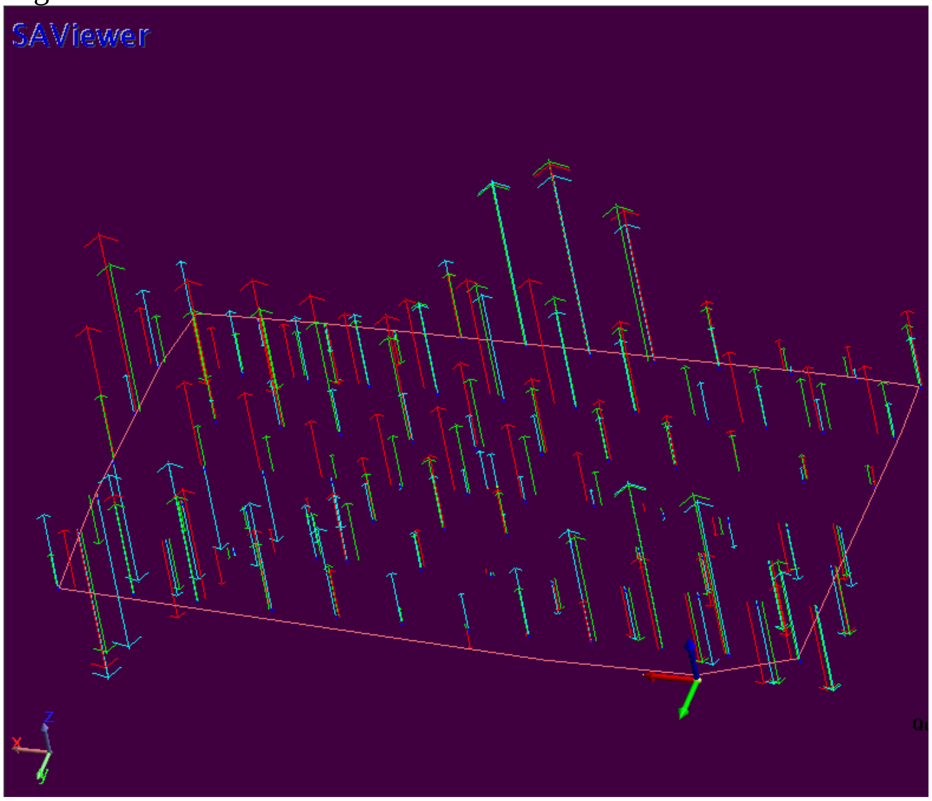


Figure 4. Discrete Point Locations Displayed in Software

## 5.2 Geodetic Systems, Inc.: V-STARS/M8 Real Time Photogrammetry System

The Geodetic Systems, Inc. (GSI) V-STARS/M8 Real Time Photogrammetry System was the second system leased for field testing purposes. The real time photogrammetry system arrived in the shipyard on 30 March 2009 and was leased for a period of three months. The first week was dedicated to training during which time the vendor was on site to provide hands on training and set up of the system in our work environment. The real time photogrammetry system was primarily used in our new panel line to measure the deformation of the plates as stiffeners are welded. Due to installation and alignment issues with the automated welding machines as described previous, manual welding techniques were the primary method in which stiffeners were welded onto the flat panels and in turn which data was collected.

Figure 5 shows the typical setup in which the real time photogrammetry was set up. In this particular instance, the panel was set to the side of the panel line for convenience and other logistical reasons. The two photogrammetry cameras can be seen near the top of the frame on opposite ends of a 20 foot long ¼" diameter square aluminum tubing piece. This piece was affixed to a man lift so it could be positioned over the top of the work area. The cameras were tethered via cabling to a control box which was in turn connected to the laptop computer. The cameras use lithium ion batteries and are wireless capable making for a nice portable setup. However, due to internal Northrop Grumman Information Technology and DoD regulations, the wireless setup was not approved for our field testing purposes, hence the project made due with the hard wired setup. Also of note with this particular setup while the man lift made for convenience in our particular setup, this would most likely not be suitable for implementation in a permanent or semi permanent production environment. The most likely solution would be having the cameras mounted on either side of the gantry which holds the automated fillet welder heads. Unfortunately this potential setup was not tested due to the automated machines being inoperable at the time of testing.

Overall results with the GSI V-STARS/M8 Real Time Photogrammetry System were quite impressive. The ability to capture numerous points simultaneously while the stiffeners were in process of being welded onto the plate proved to be a feat unmatched by the other systems that were chosen for testing in this project. In addition, the setup could be automated to capture measured data from the targeting at specified time intervals. For purposes of our test we set the system to capture data every sixty seconds while several passes were made with the track welder. This again proved to be an unmatched feat with impressive results. However, those results don't come without a significant amount of preparation. Prior to any welding, the individual peel and stick retro reflective targets must be manually placed on the panel at locations that the surveyor deems valuable for gathering data. Next, special coded targets must be strategically placed about the measurement areas of interest which are used as benchmark targets of sorts that the software uses to orient itself. The project team then placed additional retro reflective targeting on the ground surrounding the targeted area used for more permanent benchmarking locations to enable the software to tie into a 'global' coordinate system from survey to survey or from picture to picture. In addition, the placement of scale bars within the measurement area is initially required to ensure the most accurate results. Finally, the placement of the two camera setup is critical to get the amount of coverage desired as well as being able to survey the retro targets are the correct angle so the camera/software can capture and process the points of interest while in turn also capturing the coded targets and 'global' targets as required. Things such as flash intensity and hence distance away from targets, line of sight issues due to structure on the panel, and angle of incidence must be carefully considered and some trial and error must take place in order to properly position the man lift and cameras to get the best results. The operator must also consider protecting the targets if they are going to be used multiple times.

Figure 5. GSI V-STARS/M8 Real Time Photogrammetry System

A description of the real time data acquisition setup is as follows. Following the careful consideration and placement of hard targeting, coded targeting, and scale bars as described above, a single camera survey as seen in figure 6 must be accomplished. Once that survey and associated analysis in the software has been completed, each target must be carefully labeled as well as the 'benchmark' targets. This allows the software to recognize which targets are of interest for determining distortion values and which targets it needs to use as reference. Next the multiple camera system must be assembled, and carefully put into place. This process all takes time, careful planning, and can be laborious and tedious. Additionally, the threat of damaged targets from survey to survey of the before, after, and during weld is constant. Damaged targets could result from being walked on, damage from the welding itself, or any number of things in a production environment that are not very welcoming to a relatively delicate retro reflective target. However, if setup properly and carefully targeted out as can be seen in Figure 7, the payoff is a legitimate real time system that can measure distortion of multiple targets which is immune to vibration. Results as viewed in the software, V-STARS, can be seen in Figure 8 where distortions as high as +/- 1" or greater were observed in this particular 0.5" plate from beginning to end process.

Figure 6. Single Camera Photogrammetry Survey

Figure 7. Targeting required for Real Time Photogrammetry

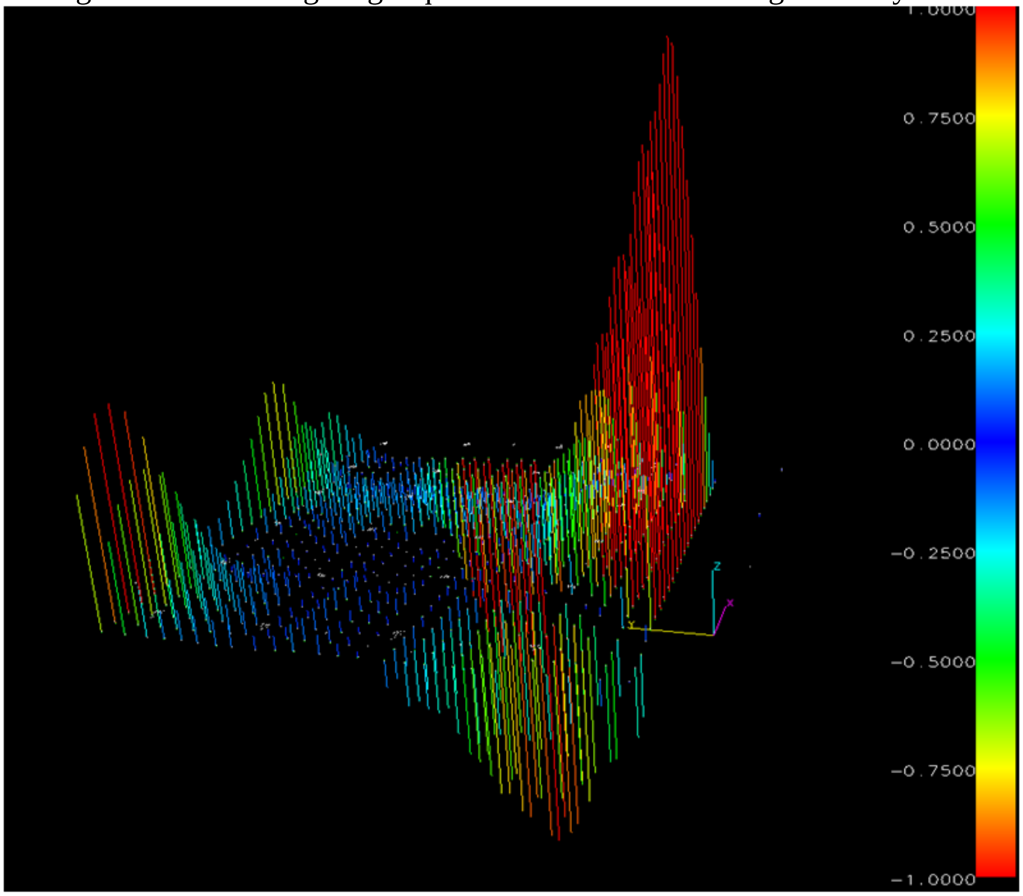


Figure 8. Distortion as Measured and Displayed in V-STARS

## 5.3 Basis Software, Inc.: Surphaser 25 HSX Laser Scanner

The final piece of equipment to be leased for field testing purposes was the Surphaser Laser Scanner. The scanner arrived in the shipyard during the week of 6 July 2009 at which time vendor training on the equipment took place to familiarize the NGSB-GC technicians with the hardware and software used for capturing and analyzing data with the Surphaser. The Surphaser Laser Scanning system is a very portable, mid range, three dimensional laser scanner. It has a practical range of about 30 meters with sub millimeter accuracy. These attributes make it attractive for the shipbuilding industry and could be used for many applications. One area of focus for the project was once again in the Panel line where distortion of flat plates was measured. The scanner, while not a real time capable solution, is intriguing due to its capability to capture a large amount of data in a short amount of time. It also has the capability to capture data with limited or no targeting required. These capabilities were very eagerly anticipated for applicability within the shipyard environment.

The Surphaser was used primarily in the panel line where its portability, relative ease and quickness of capturing data, and lack of hard targeting required where all welcomed by the technicians capturing the data. While the scanner had many positive attributes it did have a couple negative attributes including (1) not being able to provide real time data and (2) very cumbersome analysis within the software package. The survey process with the Surphaser is straightforward in that there is one connection to a laptop and one connection for power and the scanner is typically positioned on the panel to be surveyed as can be seen in Figure 9. Line of sight issues still have to be accounted for and if multiple scans need to be used and the tightest possible tolerances kept, external tooling balls can be used as reference points. These reference points can be used to stitch multiple scans together once those same points are measured with a total station; laser tracker; photogrammetry; or any highly accurate 3-D measurement equipment of choice. The technicians used 1.5" total station spheres measured with a total station for the establishment of reference points. Those points then became the hard reference points by which all scans relative to that particular setup were referenced. The canner measured those points by using solid white 1.5" tooling spheres which were interchangeable with the total station tooling spheres via the specially designed base or 'puck' made for just such use. Those pucks were hot glued in place prior to any measurements to ensure stability and were then used from survey to survey.

The aforementioned software used by the project team is Polyworks and is a product of Innovmetric Software, Inc. This software is a powerful software specializing in the inspection, manipulation, and even reverse engineering of point cloud data such as that produced by the Surphaser. This software in itself, in the author's opinion, is a detriment to the overall laser scanning solution. While the software is a powerful and effective tool for its use, it demands a significant learning curve for technicians who might be unfamiliar with it. In addition the data collected by the scanner is copious and can easily exceed a gigabyte of digital storage space per scan. Given the fact that the scanner must first collect the data with its proprietary software and then export it into a format that Polyworks will accept is cumbersome in itself. Couple this with the extremely large file sizes which in turn requires an equally large computer hard drive, and the need for a high end processor and graphics card, and this was easily the most demanding setup for computing needs among any of the equipment tested. Once this issue was identified and rectified through the lease of a laptop that could more easily handle large file sizes and data analysis, this issue was mitigated to a certain point. The fact of stitching multiple scans, identifying benchmarks within the scans, and eliminating superfluous data, still remains a challenge for a technician not familiar with this process and software combination. This is particularly true when he or she may be accustomed to manipulating more discrete point locations such as measured with a laser tracking and/or photogrammetry system. In short, one of the very attributes that makes the scanner an attractive item, collection of large amounts of data, is also one of its detriments. While this particular issue can be mitigated with the proper training, experience, and knowledge of the software, even a seasoned metrology expert utilizing this hardware/software package needs days for turnaround time as compared to the mere hours or even real time results provided by some other metrology solutions on the market and evaluated by this project.

An example of survey results analyzed in Polyworks can be seen in Figure 10. The corresponding distortion areas can be seen in Figure 9. The particular areas of interest, shown in blue and red, measure in excess of three and six inches, respectively, of before and after weld distortion. This particular survey consisted of approximately four to five scans which took approximately six or seven minutes each. That rapid collection of the data is the highlight of this system; however, the analysis that must then take place is the detriment of this system. Stitching the scans together, trimming the data collection area, and determining the distortion deltas took approximately three days of analysis time to complete. This extended analysis time was due, in part, to a learning curve associated with the technicians who were unfamiliar with the software used for analysis. Furthermore, the project leased a high end sixty four bit computer from the vendor in order to more easily scan, analyze, and store the massive amounts of data collected.

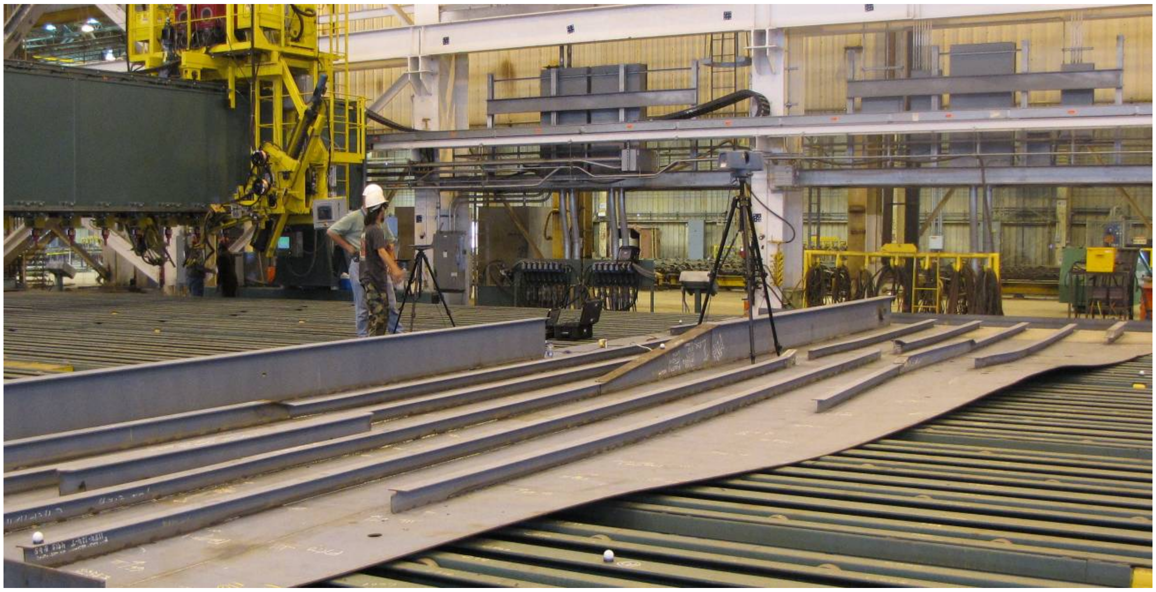

Figure 9. Surphaser Laser Scanner Surveying Plate with Structure

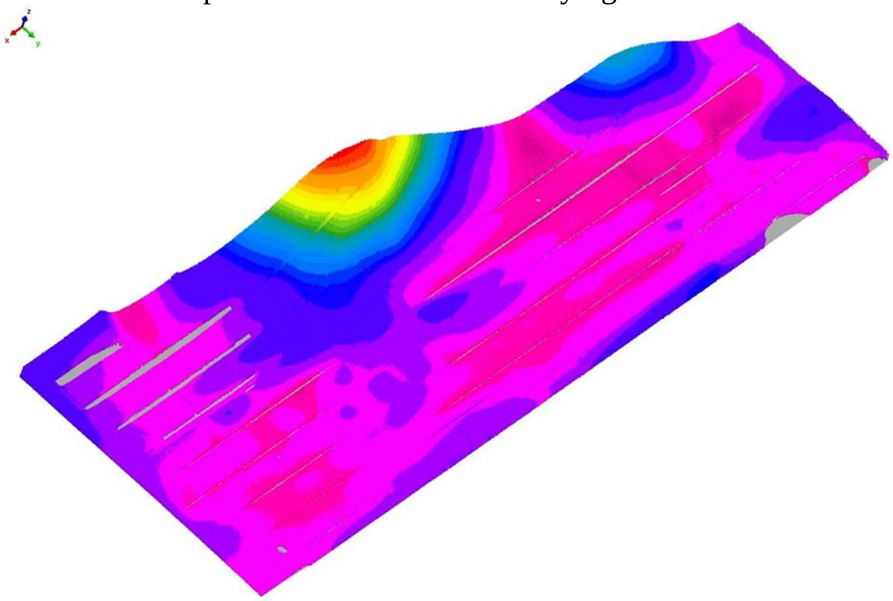

Figure 10. Analysis of Plate in Polyworks

# 6. Implementation Status

## 6.1 Applications for Three Dimensional Metrology Equipment

Northrop Grumman has committed to invest capital funds for the purchase of the API Laser Tracker 3 unit. This particular unit was field tested during the first three months (January – March 2009) of Phase II. This field testing period was crucial in gaining buy in and confidence from production personnel and management. As a result of the success and added value the laser tracker demonstrated while used during the field testing period NGSB-GC's facilities department leased that same equipment two separate times after the initial field testing period was complete. Facilities department used the laser tracker for the installation and alignment of a machine shop lathe which ultimately led to a purchase order requisition for acquiring a unit for the NGSB-GC sector. The same technicians that operated the equipment during the project field testing period used the equipment for the facilities leas and hence immediately saved the company approximately thirty thousand dollars, the cost for a vendor/supplied operator for those rental periods. Additionally, the experience that NGSB-GC technician gained while having a chance to field test the equipment gave them confidence in using the equipment which in turn gave NGSB-GC management confidence in its immediate use and impact without a significant learning curve to expect.

Additional applications of the laser tracker along with a description of their immediate implementation capability will be detailed in the following. Table 1 lists a broad spectrum of applications for three dimensional measurements. Return on investment calculations will also be detailed for selected items in the form of cost savings projections as documented in various six sigma project and/or discussions with supervision/management. These projections, while detailed amounts are described in the tables below, are estimates. These amounts are based on ideal scenarios and full implementation and utility of the introduced technology and processes. Implementation may be incremental and thus the realistic saving is likely to be more of a varying range rather than point estimates as outlined below. While savings are expected to be significant, the reader must keep in mind that the projected estimates and specific numbers mentioned herein are in no way what any manufacturing yard has committed nor does it represent a binding commitment by any described parties.

Table 1. Three Dimensional Measurement Applications in Shipyard Manufacturing

| Application | Potential Benefit |
|---|---|
| Pre Cut Unit Integration | Decrease overall integration time. Free up crane time, identify potential conflicts prior to physical integration. |
| Shaft Alignment | Enable earlier shaft alignment activities to take place prior to the ship being waterborne. |
| Combat System Weapon Alignment | More efficient measurement of critical alignment installed elements. |
| Manufacture of PVLS Units | Monitor and maintain critical alignment requirements. |
| Aircraft elevator | More accurate installation. |
| Universal Tie Down System | More efficient layout of bolt hole locations with Laser Tracker vs. Photogrammetry. |
| Monitoring critical alignment foundation during construction | Real time monitoring of foundations that are required to be pre-machined. |
| Establishing bore lines for rudder casting and rudder stock | Photogrammetry and Laser Tracker work to support machinery. |

#### 6.1.1 Pre Cut Unit Integration

Pre cut unit integration, sometimes referred to as “neat cut” is a method of integrating grand blocks or units with a corresponding grand block or unit such as the one seen in Figure 11. This method is distinguished by having surveyed both ends of the unit and having virtually fit those units together via software and predetermining a cut line, protrusions, and any potential conflicts prior to physically mating the two units. This method is highly desirable versus the alternative of physically moving those units into place, scribing them, burning the scribe line, and finally welding them together. The benefit of the virtual fit up is that the scribing, and burning can take place prior to the assemblies having to be moved thus saving significant amount of crane time, man-hours, and overall schedule.

Figure 11. Ship Assembly Unit

As described in Six Sigma Project # P1108, Neat Cut Units, Table 1 shows a projected savings total in excess of twenty-nine thousand hours for LPD 22, 23, and 24 hulls. The project desires to "Develop a process that consistently and continuously manufactures units with zero tolerance known as neat cut. The success of this project would enable us to move down the pathway of reducing ship build spans to the point where we could offer our customer a ship built in a year." Per the Six Sigma Project, "Savings accrue as 5%-8% savings to erection man hours." These numbers represent a significant savings over the current method of integrating units and the Laser Tracker will be integral in that process for quicker and more efficient surveys.

Table 2. Neat Cut Projected Savings for Selected Hulls (After: Six Sigma # P1108, 2007)

| Hull | Cost Centers | Accounts | Hours |
|---|---|---|---|
| LPD-22 | 815, 853 | 1108, 1114 | 11,866 |
| LPD-23 | 215, 253 | 1108, 1114 | 10,000 |
| LPD-24 | 815, 853 | 1108, 1114 | 8,000 |
| | | **Total** | **29,886** |

#### 6.1.2 Shaft Alignment

Six Sigma Project # 1309, Improve the Propulsion System Installation & Alignment Process, describes the duration of waterborne shaft alignment to be quite a lengthy process. Table 3 shows a potential reduction in the duration of waterborne alignment activities to be cut significantly and resulting in cost savings. A diagram depicting the major shaft alignment points can be seen in Figure 12. Changes which move certain critical propulsion alignment activities prior to the ship being launched can lead to significant savings. Table 4 describes the cost savings as a potential reduction in overall schedule.

Table 3. Number of Weeks Required for Waterborne Shaft Alignment (From: Six Sigma Project # 1309, 2008)

| Contract | Current Duration | Future Duration | Potential Reduction |
|---|---|---|---|
| LPD/LHA | 26 | 12 | 14 |
| DDG | 26 | 15 | 11 |
| NSC | 16 | 10 | 6 |

Table 4. Projected Savings Resulting from more Efficient Shaft Alignment (After: Six Sigma Project # 1309, 2008)

| Contract | Schedule reduced (weeks) | Schedule Reduction Calculation | Savings as a percentage of vessel labor |
|---|---|---|---|
| LHA 6 | X | Y FTE/wk * 40mh/wk * X schedule reduction* rate per hour | 0.30% |
| LPD | X | Y FTE/wk * 40mh/wk * X schedule reduction* rate per hour | 0.20% |
| DDG | X | Y FTE/wk * 40mh/wk * X schedule reduction* rate per hour | 0.40% |

### 6.1.3 Combat System Weapon Alignment

Combat system weapon alignment as applied during construction is another area that the API Laser Tracker 3 will be used for immediate implementation and incurs significant increase in efficiency and productivity. The laser tracker will replace older optical instruments, theodolites. The current theodolite method of measuring for correction of installation bias error of combat systems elements is time consuming, tedious, and prone to human error. The laser tracker can cut down on the number of personnel required as well as the time required to accomplish surveys. Additionally, the software capturing the data allows for revisiting the 'virtual' survey at a later date if need be as opposed to only having handwritten data to refer back to. The Navy's alignment personnel have recently adopted the API Laser Tracker 3 for their in fleet alignment surveys. Per an article in NAVY.mil, "The Navy expects to save more than $400,000 every year for at least the next four years by a reduction in time and labor associated with radar maintenance." (Laser, 2009) Additionally, the NSWC Port Hueneme team who implemented the alignment improvement has been awarded the 2008 Department of Defense (DoD) Value Engineering Achievement award in the Department of the Navy category as identified by the Under Secretary of Defense for Acquisition, Technology, and Logistics John J. Young, Jr. on 20 March 2009. "The command won the engineering award for its Surface Combatant Alignment Team, which introduced an innovative approach to measuring radar alignment using laser technology and a new AN/SPY-1 radar cover plate." (NSWC, 2009)

Robert Whittington, Accuracy Control Supervisor in charge of Combat System Alignment, and the author discussed the estimated savings of using the API Laser Tracker 3 as seen in Figure 13 versus the current theodolite method and plan on achieving significant savings as well. Table 5 outlines the savings expected as a result of implementing the API Laser Tracker 3 into Combat System Alignment. These numbers are, in the author's opinion, conservative given the aforementioned savings that the Navy expects to save on in fleet alignments. Additionally, other intangible measures such as lost hours due to inclement weather are not figured into the Table 5. The API Laser Tracker 3method of surveying would greatly mitigate or completely eliminate the lost hours due to inclement weather as well as the need to send a man aloft for the installation of tooling scales needed for theodolite measurement. Finally, this is a break out of only one combat system weapon element, AN/SPY-1. There are numerous elements that could be used for alignment with the API Laser Tracker 3 across nearly all classes of ships, including the next generation surface combatant.

Table 5. Savings Associated with AN/SPY-1 Combat System Alignment

| Event | Number of Personnel Required | Hours Required for event | Total Hours | Description |
|---|---|---|---|---|
| Installation of tooling scales | 3 | 16 | 48 | Tooling Scales no longer needed for use with Tracker |
| Installation of tooling stands | 1 | 20 | 20 | Tooling stands no longer needed for use with Tracker |
| Installation of Scaffolding and handrails | 1 | 8 | 8 | Scaffolding no longer needed for use with Tracker |
| Survey Time (Theodolite) | 6 | 8 X 2 nights | 96 | Subtotal of 48 hours are saved for survey time with the Tracker |
| Survey Time (Laser Tracker) | 6 | 8 X 1 nights | 48 | |
| | | Total hours saved for all events | 124 hours | |

Figure 12. Arleigh Burke Ship Class Weapon Alignment

### 6.1.4 Manufacture of PVLS Units

NGSB-GC will manufacture the Aft Peripheral Vertical Launching System (PVLS) units for the next generation surface combatant and ship them to BIW. The API Laser Tracker 3 will be used to monitor the manufacture of the corner details and their integration into the final unit. Things such as the perpendicularity of the corner details and the flatness of shell plating will be closely monitored to ensure that requirements are met. Hard cost savings are difficult to quantify in this particular instance due to the lack of any baseline data; however, significant cost avoidance savings can be expected. Any rework associated with the difficult to manufacture PVLS units would be extremely costly and time consuming and potentially detrimental to meeting delivery schedules.

# 7. Procurement Specifications

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API PRODUCT SPECIFICATIONS R0409-EN

Tracker3™ 15-40-60

| Parameter | Specification |
|---|---|
| **Range of Measurements** | |
| Linear Range (diameter): | T3-15 30 meters (98 feet)<br>T3-40 80 meters (262 feet)<br>T3-60 >120 meters (>400 feet) |
| **Angular Range** | |
| Azimuth: | ± 320º (640º End to End) |
| Elevation: | + 77º / -60º |
| Angular Resolution: | ± 0.018 arc seconds |
| Angular Accuracy: | 3.5µm/meter |
| System Resolution: | 0.1µm |
| Maximum Lateral Target Speed: | > 3 meters/sec (120 º /sec) |
| Maximum Acceleration: | > 2 g |
| Internal Level Accuracy: | ±2 arc-second |
| **Absolute Accuracy of a 3D Coordinate** | |
| Static Measurement (IFM): | ±5ppm (2 sigma) |
| **Laser** | |
| HeNe Laser (Interferometer) | Class II (eye safe) |
| Resolution: | 0.08µm |
| Accuracy: | Better than ±0.5 ppm |
| IR Laser (ADM) | Class I (eye safe) |
| Resolution: | 0.1µm |
| Accuracy: | Better than: ±15µm or 1.5ppm |
| **Weight** | |
| Tracker: | 8.5kg (18.5 lb) |
| Controller: | 3.2kg (7 lb) |
| **Dimensional Envelope** | |
| Tracker: | 185mm x 190mm x 360mm<br>(7.3 in x 7.5 in x 14.2 in) |
| Control Box: | 110mm x 160mm x 310mm<br>(4.3 in x 6.3 in x 12.2 in) |
| **Environmental** | |
| Air Temperature: | -10ºC to > 45ºC (14ºF to > 113ºF) |
| Barometric Pressure : | 580 mmHg - 800 mmHg |
| Relative Humidity: | 10-95% Non-condensing |
| Altitude: | 3000 Meters (9842.49 ft) |

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Figure 13. API Laser Tracker 3 Specifications (From: API, 2009)

# 8. Summary

The purpose of the Hull Fairness and Accuracy Control Project is to address increased requirements for the Navy's future surface combatant ship. First, a baseline of current requirements, tools, and methodologies being used were taken and scrutinized. Those results were compiled into a gap analysis to document areas needed for improvement in order to meet a more stringent requirement. Those results included the investigation into the latest tools and methodologies currently on the market and used in industry and how to apply those lessons learned into the shipyards manufacturing the next generation surface combatant. Once the research was complete, a down selection of tooling was made for the purpose of field testing the equipment in a shipyard manufacturing environment. The resulting field testing periods were invaluable for the observation and evaluation of the three down selected pieces of equipment. This field testing and project results ultimately led to the purchase of a laser tracker by NGSB-GC.

The original intent of the project was focused specifically on the increased requirement of the future surface combatant, and the project evolved with the acquisition strategy of the ship itself. While the Department of Defense's acquisition strategy ultimately led to the procurement of several hulls which are to be built by BIW, the bulk of this project is focused on technology to be utilized in the panel line at the NGSB-GC facility. This is where, in the author's opinion, most hull distortion is introduced. If technology, through real time or near real time analysis, can pinpoint location and magnitude of distortion then it can be mitigated by craftsmen on the floor and/or engineering personnel through the control of heat input for the automated welders and/or tailored welding processed for a specific material and thickness combination of shell plating. The field testing periods proved useful for identifying the equipment that could be most effective for meeting the described needs. The described results will require being embraced by the implementing shipyard to be effective. Additionally, tailoring may be required for use in a particular manufacturing environment and buy in from both production and management is critical.

The three pieces of equipment evaluated in phase II of this project each had positive and negative aspects relative to their applicability and implementation within a shipyard manufacturing environment. During the field testing periods, each piece of equipment was evaluated on several key aspects critical for implementation and utility within the specified environment. Key aspects include but are not limited to: portability, turnaround time for data analysis, accuracy, and ease of implementation. The next paragraphs will describe these three field tested pieces of equipment and their associated positive and negative features. Also described is the rationale that led to the ultimate purchase of one piece of equipment.

The first piece of equipment brought in for a three month field test was the API Laser Tracker 3. This piece of equipment operates much like a total station or theodolite, only much more accurately. The field test unit was controlled by third party software, Spatial Analyzer, which NGSB-GC technicians had prior training and experience with. This software/hardware combination allowed for distortion deltas at discrete point locations to be quickly and easily identified. The ability to permanently mount benchmark location strategically around the work area ensured repeatable data from survey to survey and day to day. It has a workable range of approximately eighty meters which ensured that any one setup was usually only limited by line of sight. These attributes also allowed the equipment to be versatile and easily used in other manufacturing areas. These attributes, coupled with the fact that the technicians were comfortable with the packaging and size of the equipment and familiar with the software driving it, made it a favorite tool among the technicians to use. The one negative item that stands out with the laser tracker is its inability to measure multiple points simultaneously. The nature of measurements taken with the laser tracker is suited to discrete points. Also, those points measured must have a physical target (SMR) located at the point of measurement. This could be a hindrance if one needs multiple points in a broad area measured simultaneously with access only to a single instrument.

The second piece of equipment leased for field testing was GSI's V-STARS/M8 photogrammetry system. This system is unique in that it can capture multiple targets simultaneously and provide instant results via a dual camera setup. This can be invaluable for shop floor on the fly adjustment. That type of scenario, in the author's opinion, is ideal for distortion analysis on the panel line. That type of multiple target data analysis performed in real time does not come without challenges, however. Hard targets were required to be manually placed in the form of stick-on retro reflective dots, the GSI proprietary software, V-STARS, requires meticulous setup, a single camera survey must be accomplished prior to the multi camera survey, coded targets and reference targets must be carefully placed, and finally the two cameras must be carefully positioned overhead for optimal target coverage and optimal line of sight consideration. While the results are ideal for monitoring distortion, the aforementioned challenges were ultimately too much for this system to be practical under the field testing conditions.

The third and final piece of equipment field tested during phase II of the project was the Surphaser Laser Scanner. This piece of equipment proved to be efficient in its data collection but inefficient in its data analysis. This particular instrument could collect massive amounts of data points while requiring virtually no hard targeting. This massive amount of data collection, however, proved to be the biggest hindrance of this system. First, the data was collected via the hardware manufacturer's proprietary software, SurphExpress, then exported into a file format that could be imported into a third party software, Polyworks. Finally, the data must be trimmed and/or merged (if multiple scans were required) before any distortion analysis could be made. This analysis turnaround time would be, at a minimum, twenty four hours. While the ease and relative quick scan time of massive amounts of data made this particular instrument the most efficient at data collection, its data analysis time and lack of real time results made it an impractical choice for monitoring and providing feedback on distortion analysis in the dynamic manufacturing environment. These challenges coupled with the need of a high end sixty four bit computer platform further emphasized the reason this system was not ideal for implementation given the project's original intent.

The API Laser Tracker 3 was selected for capital purchase by NGSB-GC for its versatility, relatively small footprint and portability, familiarity of software, accuracy, and overall ease of use within the manufacturing environment. Additionally, this piece of equipment was rented by NGSB-GC after the original project lease terms were complete for the purpose of calibration and installation of a machine shop lathe. This demonstrated the buy in and commitment from operations and management which is critical for the full utilization of the equipment. This confidence and need for the equipment ultimately led to the purchase of the laser tracker. Its implementation will be immediate on jobs ranging from combat system weapon alignment to maintenance and calibration of precision machinery.

NGSB-GC plans to invest its capital dollars for the purchase of an API Laser Tracker 3 unit. Some of the same attributes that made it a natural fit in the panel line such as portability and ease of use during the field testing period also makes it practical in a number of other applications for use throughout the shipyard. Ultimately the use of this equipment at NGSB-GC will result in significant cost savings, schedule reductions, and improved quality for current and future ships built at its shipyards or for any other shipyard willing to embrace and implement its capabilities.

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