ESTCP
Cost and Performance Report

(ER-200919)

Demonstration of an In-Situ Friction-Sound Probe for Mapping Particle Size at Contaminated Sediment Sites

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ENVIRONMENTAL SECURITY
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COST & PERFORMANCE REPORT

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ACRONYMS AND ABBREVIATIONS

ASTM	American Society for Testing and Materials
BNI	Bechtel National, Inc.
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
cm/sec	centimeters per second
CWA	Clean Water Act
DoD	Department of Defense
ESTCP	Environmental Security Technology Certification Program
FS	Feasibility Study
GSI	ground water – surface water interaction
Hz	hertz
IR	Installation Restoration
µm	micromoles
MCL	maximum contaminant level
mm	millimeter
msec	milli-seconds
NASNI	Naval Air Station North Island
NAVFAC	Naval Facilities Engineering Command
NBSD	Naval Base San Diego
PAH	polynuclear aromatic hydrocarbon
PC	personal computer
PCB	polychlorinated biphenyl
PSD	particle size distribution
psi	pounds per square inch
RCRA	Resource Conservation and Recovery Act
RI/FS	Remedial Investigation/Feasibility Study
RMS	root mean square
SED-FSP	sediment friction sound probe
SPAWAR	Space and Naval Warfare Systems Command
SSC-PAC	SPAWAR Systems Center – Pacific
SCCWRP	Southern California Coastal Water Research Project

ACRONYMS AND ABBREVIATIONS (continued)

TMDL	Total Maximum Daily Load
VOC	volatile organic compound

ACKNOWLEDGEMENTS

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EXECUTIVE SUMMARY

OBJECTIVES OF THE DEMONSTRATION

The Navy, Department of Defense (DoD), and other government and private entities are in the process of identifying, assessing, and remediating a large number of hazardous waste sites that are the result of decades of waste management practices resulting in the release of contaminants to soil, sediment, and groundwater in coastal environments. At contaminated sediment sites it is generally accepted that the affinities of contaminants for fine-grained sediment result in high contaminant concentrations in areas that are characterized by fine sediments. (Calvert, 1976; Warren, 1981) In contrast, at groundwater – surface water interaction (GSI) sites, groundwater discharge of more mobile, dissolved-phase contaminants is often associated with course grained, permeable sediment units (Fetter, 1994). Knowledge of grain size at sediment study sites can provide lines of evidence that can be applied to identify potential areas of contaminated sediment and contaminant discharge zones.

Field surveys for grain size can require a full sampling regime including substantial analytical costs. The sediment friction-sound probe (SED-FSP) technology was proposed as a remedy for quickly and cost effectively acquiring grain size information. The overall objective of this project was to field demonstrate the effectiveness of the SED-FSP for direct, in-situ measurement of grain size at contaminated sediment and GSI sites. The objective was accomplished through:

- Development of a commercial prototype friction-sound probe,
- Verification of sensor performance in the laboratory, and
- Field demonstration and validation at varying application regimes to delineate.

Three types of sites were selected to field demonstrate the technology: (1) a GSI site, (2) a contaminated sediment site, and (3) a contaminated sediment thin-layer containment cap where the vertical profiling capabilities of the technology were demonstrated.

TECHNOLOGY DESCRIPTION

The friction-sound intensity at a particle/sensor interface has been shown to be a linear function of the radius of particles in contact with the sensor surface and the velocity of the probe (Koomans, 2000). The SED-FSP technology employs this relationship to infer grain size by measuring the acoustic response as a probe with an imbedded microphone penetrates a sediment matrix. The microphone signal is processed through an on-board electronics interface package and transmitted to recording software. A pneumatic drive unit mounted on an aluminum frame assembly is used to drive the probe into the sediment bed at a controlled speed. Grain size is determined by comparing the acoustic response to responses of prepared sediments of known grain sizes, the calibrations are performed prior to the field deployment.

The unit was demonstrated at three application regimes: a contaminated sediment site, a GSI site, and a contaminated sediment sand cap. Site surveys of the areas were conducted with the SED-FSP system and responses were used to generate grain size maps. For two of the areas, the system was used to generate grain size depth profiles. Validation of the technology was accomplished by comparing SED-FSP response to laboratory validated measurements of site sediments and through comparison to previously conducted site surveys.

DEMONSTRATION RESULTS

The SED-FSP technology was demonstrated at three locations: Naval Base San Diego (NBSD) at the mouth of Chollas Creek in San Diego Bay, North Island Naval Air Station (NASNI) Installation Restoration (IR) Site 9, and the Active Capping Pilot Study Site on the Anacostia River in Washington, D.C. At Chollas Creek, 20 stations were acquired including collection of validation samples at all stations. The resulting survey showed that the largest grain sizes measuring in the medium sand range were acquired at the mouth of the creek trending to finer sediments into San Diego Bay and upstream into Chollas Creek. These results were supported by an earlier site assessment performed in 2004 by Space and Naval Warfare Systems Command (SPAWAR) Systems Center – Pacific (SSC-PAC) investigators, which found the same trends.

Two surveys were performed at the NASNI IR Site 9 location. During the first field effort, the SED-FSP was deployed at 27 locations where validation samples were collected. The SED-FSP succeeded in determining size classifications for the validation sediments to greater than 85% accuracy, in all instances where the response was not validated the SED-FSP under predicted grain size. During the second deployment at NASNI, the SED-FSP was used to survey the entire study area, which included twelve transects, nine to twelve stations per transect. The results were used to generate grain size maps of four depth layers, which were used as evidence supporting previous assessments of contaminant transport at the site. The results were also used to support the sampling plan for a comprehensive assessment of IR Site 9 that is anticipated in the near future.

At the Active Capping Pilot Study Site on the Anacostia River a sand cap that had been installed in March 2004 was investigated. The purpose of the deployment was to demonstrate the capability of the SED-FSP to acquire grain size measurements in subsurface sediments, to delineate the capping material/native sediment interface, and to provide information on the capping thickness. Of the 44 core sections submitted for validation, the SED-FSP correctly predicted 42 size classification results. The SED-FSP identified the subsurface capping material/sediment interface and confirmed that its thickness and boundaries have remained intact. This was confirmed with the sediment cores that showed that the capping material remained intact with little dispersion beyond the cap boundaries or into the underlying native sediment.

IMPLEMENTATION ISSUES

The costs associated with implementation of the technology are similar to costs associated with sediment sampling deployments. The key cost drivers are labor, field deployment costs, transportation/shipping, and capital equipment costs. The capital costs for the technology would be expected to be recovered quickly as they are low. The demonstrations were performed at full-scale, therefore scale-up is a non-issue. Costs related to sample analysis relate to data reduction by the user by spreadsheet or other processing software, costs are not incurred for sample analysis as the SED-FSP performs this function in real-time.

Prior to each of the field demonstrations the SED-FSP was calibrated using prepared sediments of known grain sizes. When employed in the field it was found that the system tended to under predict grain size based on analysis of validation samples. Recalibration of the system using a limited number of site sediments as calibration samples resulted in the unit performing within the performance metrics. Therefore site specific calibrations are required using site sediments.

Field testing of the unit confirmed applicability of the technology where fine sediments were differentiated from sandy sediment and between sub-classifications of sands; sediments in the clay range (< 3.9 micromoles [µm]) were not acquired either as a SED-FSP response or as results of laboratory analysis of site samples. Laboratory testing also showed that the SED-FSP did not resolve or accurately predict sizes of this range and smaller. The unit should therefore be considered for use where differentiation of sands and fines are required. Differentiation of silt (3.9 - 63 µm) and clay sizes was not validated.

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1.0 INTRODUCTION

1.1 BACKGROUND

The Navy, Department of Defense (DoD), and other government and private entities are in the process of identifying, assessing, and remediating a large number of hazardous waste sites that are the result of decades of waste management practices resulting in the release of contaminants to soil, sediment, and groundwater in coastal environments. Areas of potential concern at these sites are identified by conducting chemical, toxicological as well as geophysical (including grain size analysis) surveys during the characterization phase of the site assessment. At contaminated sediment sites it is generally accepted that the affinities of contaminants for fine-grained sediment result in high contaminant concentrations in areas that are characterized by fine sediments. (Calvert, 1976; Warren, 1981; Förstner, 1989; Santschi et al., 1997) In contrast, at groundwater – surface water interaction (GSI) sites, groundwater discharge of more mobile, dissolved-phase contaminants is often associated with course grained, permeable sediment units (Fetter, 1994). In combination with other groundwater tracers (i.e., temperature and salinity; Chadwick and Hawkins, 2008), grain size can provide an important line of evidence for identifying potential discharge zones.

At most contaminant impacted sites grain size analysis is typically carried out only as part of an overall suite of physical, chemical and toxicological analyses during the characterization stage of an remedial investigation/feasibility study (RI/FS). Determination of sediment grain size is normally based on core or grab samples collected in the field and analyzed in the laboratory. Field collection of these samples can be expensive, requiring boats and crews, load handling equipment, sampling gear, sample handling and storage, and custodial management. The traditional analytical method for measuring grain size is a time and labor intensive process. Sand, gravel and larger particles are separated with sieves, silts, and clays are determined by sedimentation through use of pipettes (Plumb, 1981) or hydrometer (American Society for Testing and Materials [ASTM] D 422-63). As alternatives, various optical techniques, electro-resistance (Coulter Counter), and laser diffraction methods are available for acquisition of particle size distributions in the laboratory after collection, handling and processing of the sediments. While sediment systems have inherently large spatial variability and generally require relatively dense sampling, sampling density by traditional methods is generally limited because collection and analyses activities are labor intensive and costly. The turnaround time between sample collection and results can also be excessive, especially in the context of adaptive sampling strategies such as the Triad approach (Crumbling, 2004). From the perspective of accurate, fast, adaptive assessments, new technologies are required. There is a general need for a rapid, cost-effective screening method for grain size characterization at contaminated sediment and GSI sites to reduce time and cost and to promote adaptive assessment and management strategies.

1.2 OBJECTIVES OF THE DEMONSTRATION

The overall objective of this project was to field demonstrate the effectiveness of a sediment friction-sound probe (SED-FSP) for direct, in-situ measurement of grain size at contaminated sediment and GSI sites. The objective was accomplished through:

- Development of a commercial prototype friction-sound probe,
- Verification of sensor performance in the laboratory, and
- Field demonstration and validation at varying application regimes to delineate areas of potential contamination and ground water discharge zones.

Three types of sites were selected to field demonstration the technology: (1) a GSI site, (2) a contaminated sediment site, and (3) a contaminated sediment thin-layer containment cap. The demonstration sites provided a broad range of grain size conditions ranging from predominantly sandy to predominantly fine and a site where delineation of subsurface sediments could be evaluated.

1.3 REGULATORY DRIVERS

Contaminated sediment and contaminant movement by GSIs are regulated under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), established to provide a legal framework for cleanup of contaminated sites. Contaminant entry points may also be covered by the Clean Water Act (CWA) Total Maximum Daily Load (TMDL) process that set limits on point and non-point source pollution-loading that do not meet, or are not expected to meet, state water quality standards. The Resource Conservation and Recovery Act (RCRA) may be applied by regulatory agencies for corrective actions at DoD sites or facilities impacted by past treatment, storage, and disposal practices. State and federally regulated sites often have to meet levels such as a maximum contaminant level (MCL) at a point of compliance in order to conservatively protect surface water.

2.0 TECHNOLOGY

2.1 TECHNOLOGY DESCRIPTION

Friction-sound is an intriguingly simple and robust technique that can be employed for measuring soil and sediment grain size. The relationship of friction-sound intensity at a particle/sensor interface has been shown to be a linear function of the radius of particles in contact with the sensor surface and the velocity of the probe (Koomans, 2000). Experimental evaluation of acoustic penetrometers for soils showed that the amplitudes of the acoustic emissions from a surface probe moving through or over the soil medium is a function of the median grain size, particle packing, and of the penetration rate of the probe in the soil.

The SED-FSP system employs an acoustic sensor at the tip of a meter long stainless steel probe that responds to friction sound intensity as the probe penetrates the sediment substrate. The probe is a ½ inch diameter tube with a probe tip approximately 1¼ inches long screwing into a ¼ inch Delrin section containing an acoustic microphone; the Delrin section that serves to acoustically isolate the microphone from the rest of the SED-FSP assembly (Figure 1). The microscope signal is fed through the probe to an on-board electronics interface package that processes the signal and transmits the processed data to recording software. The main components of the SED-FSP probe are shown in Figure 2, including the probe tip, Delrin isolator with embedded microphone, probe interface, and electronics interface.

Figure 1. Probe tip – microphone embedded in Delrin isolator.

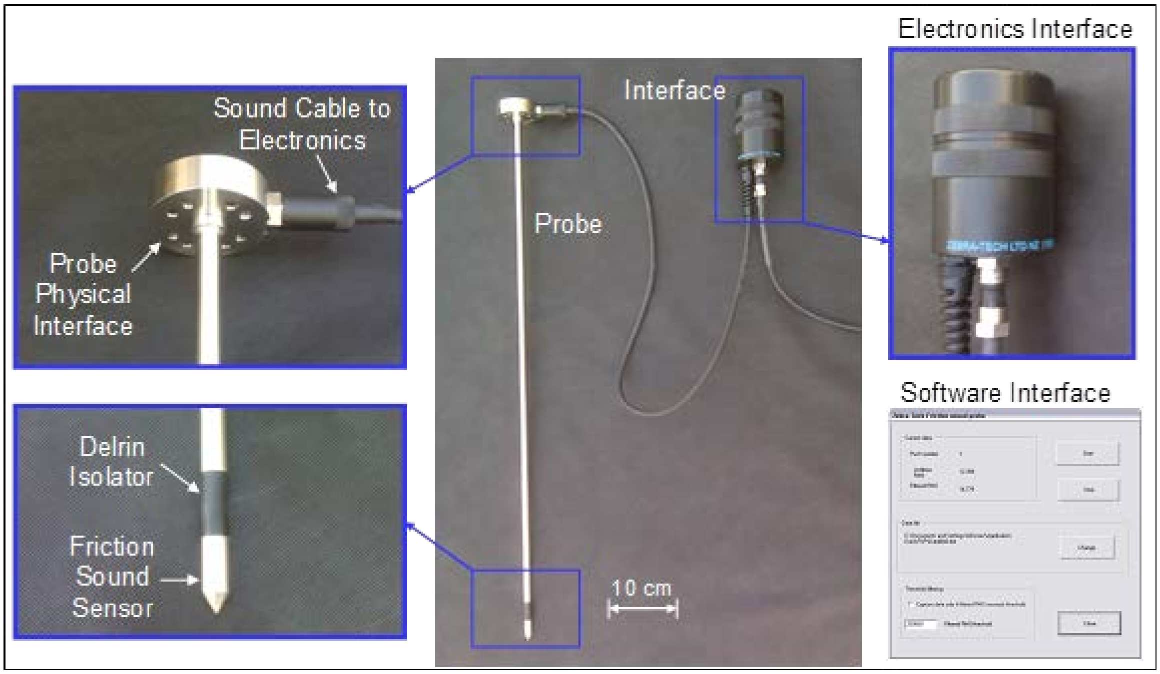

Figure 2. Commercial prototype SED-FSP.

The stainless steel probe is driven into the sediment bed by a pneumatic piston/cylinder drive unit vertically mounted onto an aluminum frame assembly (Figure 3). The total height of the system is approximately 7½ feet, the frame assembly footprint is approximately 4 feet by 4 feet square. The pneumatic system operates at between 85 – 120 pounds per square inch (psi) using a multiple-valve control mechanism remotely controlled by an operator from a deployment platform. The compressed air source can be a portable air compressor or compressed air tanks in environments where a compressor isn't available (e.g., diver tanks were used during one field deployment).

When fully retracted the probe tip is in contact with the sediment surface, as the pneumatic cylinder is activated the SED-FSP probe tip extends downwards and penetrates the sediment bed at a constant speed (5.5 to 4.6 centimeters per second [cm/sec]) to a depth of 2 feet acquiring an acoustic signal during full penetration of the sediment. An onboard camera attached to the frame (not shown in the figures) provides real-time video to the operator to ensure that surface obstructions are not present and that the probe has not encountered subsurface obstructions and penetration is occurring at a constant rate.

The acoustic signal generated at the probe tip is transmitted to an onboard electronics package that filters microphone output and transmits a processed signal to data storage and processing software located on the operators personal computer (PC). The electronics package captures microphone output and determines an average root mean square (RMS) sound amplitude over a predefined time interval. In the current configuration, the processed signal is output at intervals of 160 milli-seconds (msec), equivalent to a signal rate of 6.25 hertz (Hz).

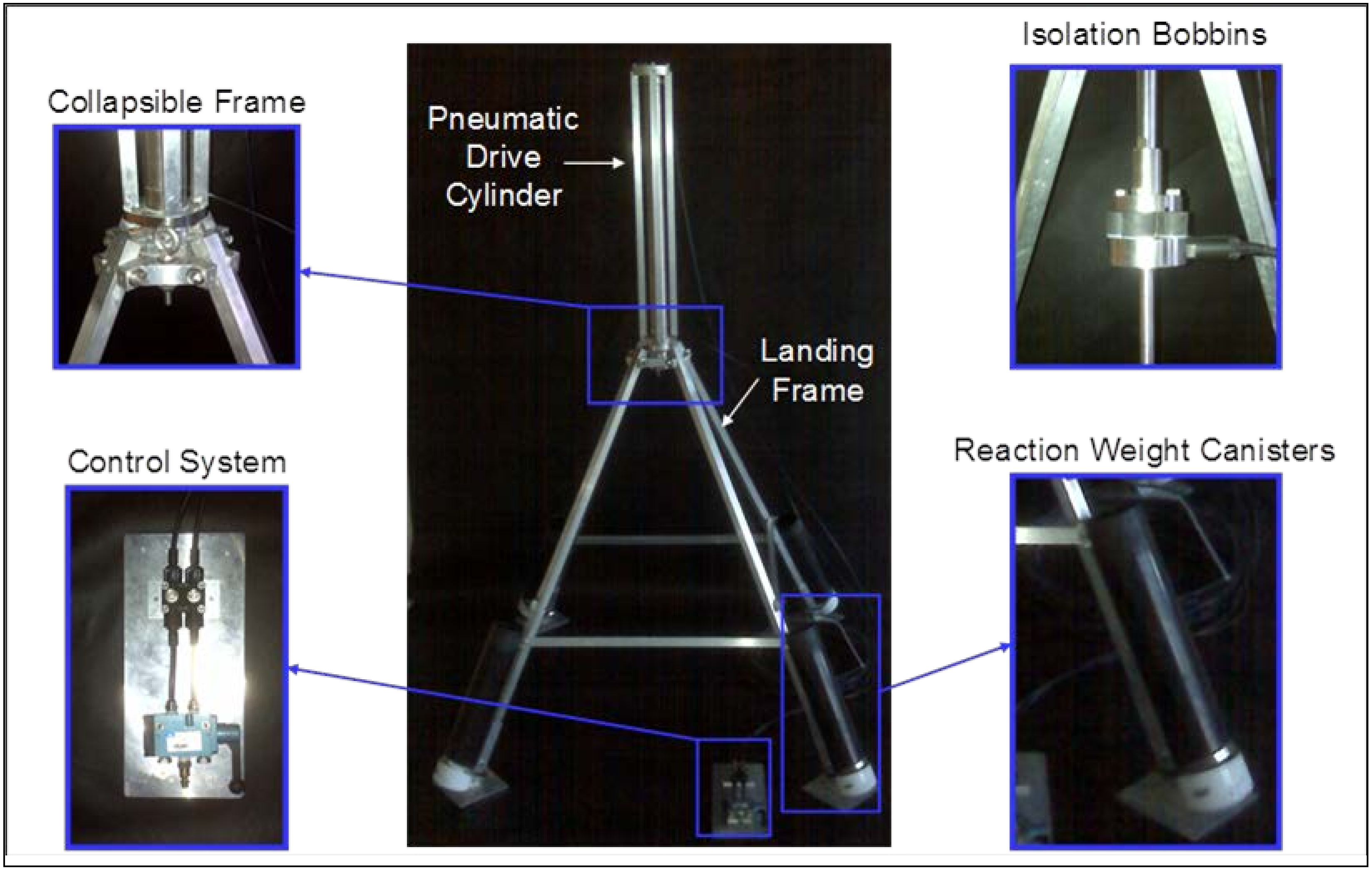

Figure 3. SED-FSP and driving system assembly.

For determination of surface sediment grain size the SED-FSP response output associated with the top sediment layer is identified and an average of the responses is calculated. For measurements of subsurface sediments, the SED-FSP output is associated to subsurface depth through use of penetration speed and the acoustic response time signature. The SED-FSP electronics package transmits the processed data to a PC laptop computer running FSP-Talk software developed by the SED-FSP commercial developer, Zebra-Tech, Ltd. of Nelson, New Zealand (Figure 2). FSP-Talk stores the processed signal to data files for later processing and displays a plot of the processed signal as a function of time.

2.2 ADVANTAGES OF THE TECHNOLOGY

The development of this capability provides at least three significant advantages over current approaches. There is a potential cost savings associated with the ability to quickly and easily map grain size distributions. The cost savings stem from the reduced sampling time, sample handling, shipping, and analytical efforts. The ability to obtain data while in the field creates the opportunity for adaptive sampling in accordance with applicable or relevant and appropriate requirements (i.e., the Triad approach) and other adaptive management principles, leading to a strong potential for more focused and thus less expensive characterization for both contaminated sediment and GSI sites. Finally, the ability to rapidly obtain vertical profiles of grain size provides the potential to cost effectively assess the implementation and stability of certain sediment remedies such as thin-layer caps and amendments that have distinctive grain size properties relative to the native sediment. Thus, specific advantages of the SED-FSP over traditional grain size analytical techniques include:

- Rapid, cost effective, in-situ grain size surveys of bottom sediments for particle sizes ranging from sand to silt/clay,
- Support for adaptive management strategies such as Triad to streamline site characterizations, and
- Improvements in cost and efficiency associated with the ability to rapidly characterize the implementation and stability of certain sediment remedies such as thin-layer capping.

2.3 LIMITATIONS OF THE TECHNOLOGY

Potential technical risks identified in association with field demonstration and commercialization of the SED-FSP technology include:

- The SED-FSP system output is limited to a single characteristic indicator of grain size, a size distribution or other statistical parameters are not measured. SED-FSP output is mean grain size diameter or an associated size classification (e.g., Wentworth size class).
- Experience to date indicates that a laboratory calibrated SED-FSP will underestimate grain size during field deployments. The solution is to field calibrate the SED-FSP with site sediments. Global empirical calibration from additional sites may prove robust enough to use across other sites.

- Controlling for deployment effects such as non-uniform push velocity and background noise.

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3.0 PERFORMANCE OBJECTIVES

The performance objectives (Table 1) focused on rapid, in situ classification of surface sediment type (quantitative) over a broad range of applications and conditions (qualitative). The quantitative performance was assessed by direct comparison of SED-FSP results to grain analysis by a standard method by a contracting laboratory (ASTM D-422). The qualitative performance was evaluated through assessment over three varying application regimes, which were the basis for demonstration site selection.

Table 1. Performance objectives for the SED-FSP demonstration.

Performance Objective	Data Requirements	Success Criteria
Quantitative Performance Objective		
Rapidly classify surface sediment substrates in-situ	SED-FSP friction sound data and corresponding particle size distribution (PSD) data over a range of sediment types.	SED-FSP correctly classifies sediments based on particle size statistics.
Qualitative Performance Objective		
Demonstrate applicability for a range of potential applications.	Calibrated SED-FSP friction sound data over a range of different applications including GSI, contaminated sediment, and thin-layer cap.	SED-FSP data useful in delineating the extent of discharge, contamination, and/or cap placement.

3.1 OBJECTIVE 1 – RAPIDLY CLASSIFY SURFACE SUBSTRATES IN SITU

The effectiveness of the technology is a function of the degree to which the sediment substrate can be rapidly and accurately classify sediment grain size.

3.1.1 DATA REQUIREMENTS

The data requirements were the output of the SED-FSP and grain size verification results obtained by laboratory analysis. The sediment samples were collected simultaneously with SED-FSP deployment by a diver using standard coring methods to ensure that the SED-FSP probe deployment and the sediment core collections were collocated. The laboratory results were used to determine a size classification based on the Wentworth scale of grain size classification (Wentworth, 1922), the calibrated SED-FSP response was the basis for determining a corresponding Wentworth size classification.

3.1.2 SUCCESS CRITERIA

Quantitative success was based on the SED-FSP ability to correctly classify sediments according to Wentworth size classification of grain size. Specific measures of classification success included reliability, efficiency, and specificity. Reliability measures the percentage of correctly classified stations in comparison to the total number of stations. For each grain size classification level (sand, silt, clay), efficiency measures the percentage of correctly classified stations at that level in comparison to the total number of stations classified in that level. Similarly, for each classification level, the specificity measures percent of correctly classified stations in that level out of the total number of stations that actually fall in that level. The project goals for reliability, efficiency, and specificity were 80%.

3.2 OBJECTIVE 2 – DEMONSTRATE APPLICABILITY FOR A RANGE OF POTENTIAL APPLICATIONS

The relevance of the technology to DoD depends to a large degree on the range of applicability over a range of site characteristics and conditions.

3.2.1 DATA REQUIREMENTS

The data requirements for this objective required SED-FSP demonstration over a range of different applications including a GSI site, a contaminated sediment site, and a thin-layer cap site. For GSI sites, the probe differentiated coarse-grain units that represented potential preferential groundwater flow pathways. For contaminated sediment sites, the probe delineated areas of high fines content, which are generally co-associated with high contaminant levels. At the thin-layer cap site, the probe was used to profile the location and thickness of the capping material.

3.2.2 SUCCESS CRITERIA

Qualitative success was determined by the ability of the SED-FSP to provide a site survey map of grain size or similar information to delineate the extent of potential discharge zones, extent of potential contamination, and/or cap placement and stability as determined by comparison to results obtained by standard methods of PSD analysis of sampled sediments.

4.0 SITE DESCRIPTION

Demonstration site selection was based on spanning three application regimes; contaminated sediments, a GSI zone, and a remedy placement (thin-layer containment cap). The sites selected for the technology demonstration were Naval Air Station North Island (NASNI) – Installation Restoration Site 9 (GSI), Naval Base San Diego (NBSD) – Chollas Creek (contaminated sediment), and a contaminated sediment sand cap located at the Anacostia River Pilot Cap Study site in Washington, DC.

4.1 INSTALLATION RESTORATION SITE 9 - NAVAL AIR STATION NORTH ISLAND

NASNI Installation Restoration (IR) Site 9 is a GSI site where volatile organic compounds (VOCs) are discharging to San Diego Bay (Bechtel National, Inc. [BNI], 1998). The SED-FSP field demonstration at NASNI was integrated into a broader characterization work plan being conducted to evaluate alternative remedy technologies and development of cleanup goals. (Naval Facilities Engineering Command [NAVFAC], 2009). The broader characterization study will acquire additional soil and groundwater data necessary to satisfactorily evaluate remedial technologies and develop cleanup goals supporting an updated feasibility study (FS).

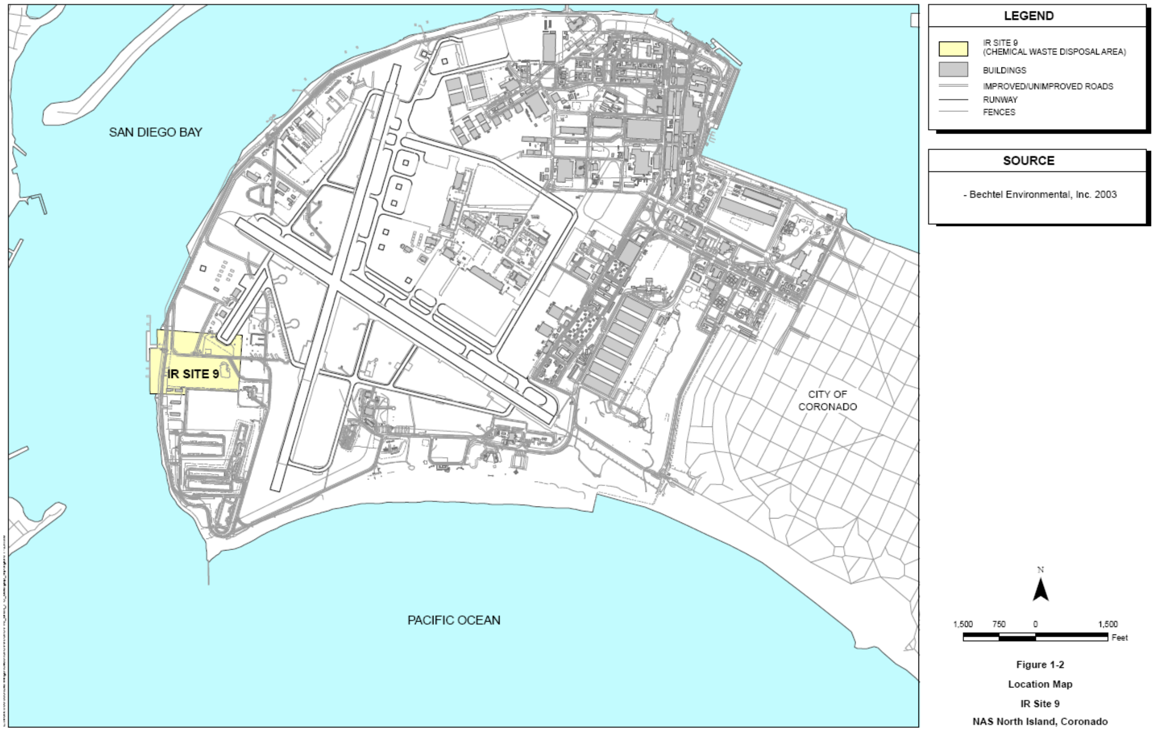

Figure 4. IR Site 9 at NASNI.

4.2 CHOLLAS CREEK TMDL SITE – NBSD

On October 26 - 28, 2010, the SED-FSP was deployed at 23 locations at the mouth of Chollas Creek in the San Diego Bay. Toxicity observed in Chollas Creek led the Regional Water Quality

Control Board to add this watershed to the CWA 303(d) list of impaired waterbodies. Conditions at the Chollas Creek site were well suited for demonstrating the capability of the SED-FSP to identify areas of high fines content using associated with areas of high contaminant concentrations. The demonstration field effort was the first use of the technology in an actual field environment.

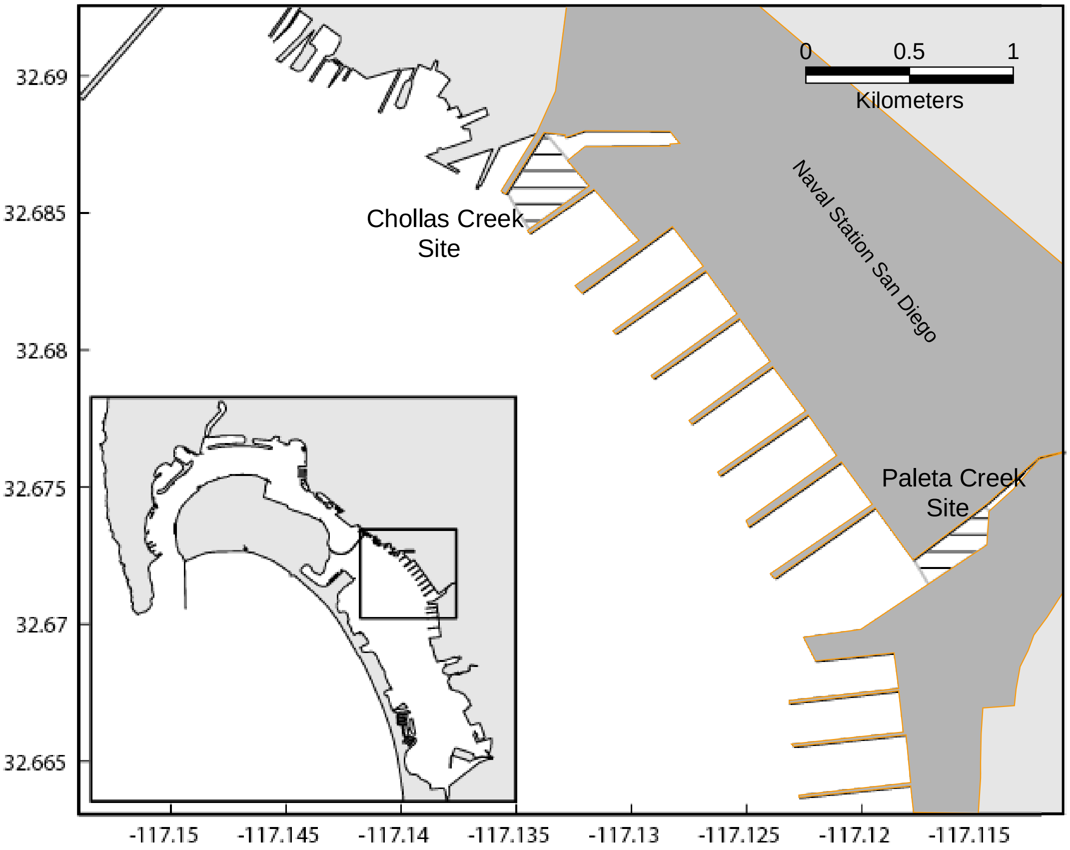

Figure 5. Chollas Creek site, NBSD.

4.3 ANACOSTIA RIVER ACTIVE CAPPING PILOT STUDY SITE, WASHINGTON, D.C.

The Anacostia River, located in Maryland and the District of Columbia, has been identified as one of the 10 most contaminated rivers in the country and also one of three areas of concern for the Chesapeake Bay watershed. Historic industrial, municipal, and military activities have resulted in toxic levels of polynuclear aromatic hydrocarbons (PAH), polychlorinated biphenyls (PCB), metals, and other contaminants. In March 2004, innovative contaminated sediment cap materials were placed in the Anacostia River to demonstrate their applicability for management of sediment contaminants (Figure 6), including a thin-layer sand cap that was included for purposes of comparison. The sand cap, located on the north-east corner of the study area, was selected for demonstration of the technology to delineate between the capping material and underlying (or overlying) native sediments.

Figure 6. Anacostia River Active Capping Pilot Study Site, Washington, D.C.

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5.0 TEST DESIGN

5.1 EXPERIMENTAL CONCEPTUAL DESIGN

The objective of this project was to assess the effectiveness of the SED-FSP for in-situ measurement of grain size over a broad spectrum of sediment grain size conditions. The SED-FSP performance was assessed by comparison of the SED-FSP output to verified laboratory grain size results over a range of sediment types at three application regimes. The application regimes were a contaminated sediment site (Chollas Creek, NBSD), a ground water/surface water interaction site (NASNI IR Site 9), and a contaminated sediment thin-layer sand cap (Anacostia River Active Capping Pilot Study site, Washington, D.C.).

5.2 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

The SED-FSP probe unit is self-contained requiring a deployment platform where a compressed air source, power source and an operator with laptop computer and video monitor are located. The deployment vessel used for the NBSD Chollas Creek and IR Site 9 locations was a 40 foot survey vessel belonging to the Environmental Sciences and Applied Systems Branch of Space and Naval Warfare Systems Command (SPAWAR) Systems Center – Pacific (SSC-PAC). At the Anacostia River site, the deployment platform was a 16 feet by 8 feet pontoon platform with a 12 foot recreation boat rental for support. Load handling capabilities are required to deploy the SED-FSP from the platform, at the Anacostia River location this was a 6 foot davit with a hand crank. With the exception of electrical power and a compressed air source, there are no other components that are required to operate the system.

5.3 FIELD TESTING SCHEDULE

The field deployment dates are shown in Table 2 below, differing only in the number of days on the water, which was determined by the scale of the effort and sampling resolution.

Table 2. Field demonstration activity schedules.

NBSD, Chollas Creek					
	Field Deployment Dates				
Field Activities	25-Oct-10	26-Oct-10	27-Oct-10	28-Oct-10	29-Oct-10
Field/Support Vessel Mobilization	■				
SED-FSP and Drive System Staging	■				
SED-FSP Implementation/Survey		■	■	■	
SED-FSP Data Collection and Analysis		■	■	■	
Verification Sediment Sampling		■	■	■	
SED-FSP Demobilization					■
Sample Processing and Shipment					■

Table 2. Field demonstration activity schedules (continued).

North Island Naval Air Station IR Site 9					
Field Activities	Field Deployment Dates				
	10-May-11	11-May-11	12-May-11	13-May-11	14-May-11
Field/Support Vessel Mobilization		■			
SED-FSP and Drive System Staging		■			
SED-FSP Implementation/Survey			■	■	
SED-FSP Data Collection and Analysis			■	■	
Verification Sediment Sampling			■	■	
SED-FSP Demobilization					■
Sample Processing and Shipment					■

Anacostia River Thin-Layer Cap Site					
Field Activities	Field Deployment Dates				
	13-Feb-12	14-Feb-12	15-Feb-12	16-Feb-12	17-Feb-12
Field/Support Vessel Mobilization	■	■			
SED-FSP and Drive System Staging		■			
SED-FSP Implementation/Survey			■		
SED-FSP Data Collection and Analysis			■		
Verification Sediment Sampling			■		
SED-FSP Demobilization				■	
Sample Processing and Shipment				■	

5.4 SAMPLING RESULTS

The validation samples collected during the three field deployments are summarized in Table 3 below. The table identifies the number and types of samples collected and submitted for grain size analysis by the contracting laboratory.

Table 3. Verification sampling summary, all deployments.

Matrix	Type	Number of Sample	Analyte	Location
NBSD Chollas Creek (contaminated sediment site)				
Sediment	Homogenized core or grab (upper 15 cm)	23	Grain size analysis	20 SED-FSP deployment locations and 3 replicate validation stations
NASNI Site 9 (GSI site)				
Sediment	Homogenized core or grab (upper 15 cm)	42	Grain size analysis	93 SED-FSP only stations, 27 SED-FSP deployment locations and 3 replicate validation stations.
Anacostia River Pilot Cap Study Site (thin-layer capping site)				
Sediment	Sediment core, 6-8 sections (2 inch) per core	50	Grain size analysis	24 SED-FSP deployment locations, 8 verification sampling locations, 3 replicates at 1 location

5.4.1 CHOLLAS CREEK, NBSD

Chollas Creek Survey Results

Based on the SED-FSP deployment of October 26 - 28, 2010, a contour map of grain size of the surface sediments was generated (Figure 7). The map is a survey of surface sediments defined as the top 6 inches (15 cm) of sediment, the corresponding SED-FSP responses over this depth interval were averaged to obtain the grain size measurement. The mouth of the creek, as it encounters San Diego Bay, appears to be dominated by larger particles mainly as a result of measurements obtained at two locations near the creek mouth. The rest of the area is dominated by sediment in the fines size range. In general, the results corroborate an earlier assessment conducted by SSC-Pacific in 2004 (Southern California Coastal Water Research Project [SCCWRP], 2005) that also identified larger grain sizes at the mouth of the creek.

Figure 7. SED-FSP survey results for mouth of Chollas Creek at NBSD.

5.4.2 NASNI IR SITE 9

IR Site 9 Survey Results

The deployment locations at the IR Site 9 location were along a series of 12 offshore transects that encompass the ground water discharge zone identified in previous studies (SPAWAR, 2001). The vertical profiling capabilities of the SED-FSP were used to provide grain size maps of varying depth horizons (Figure 8 and Figure 9). The contour maps created are for four sub-surface depth intervals providing a site-wide representation size classifications. The patterns are useful in understanding potential groundwater discharge pathways, especially as the ground water approaches the shallow sediment zone (within 2 feet of the interface).

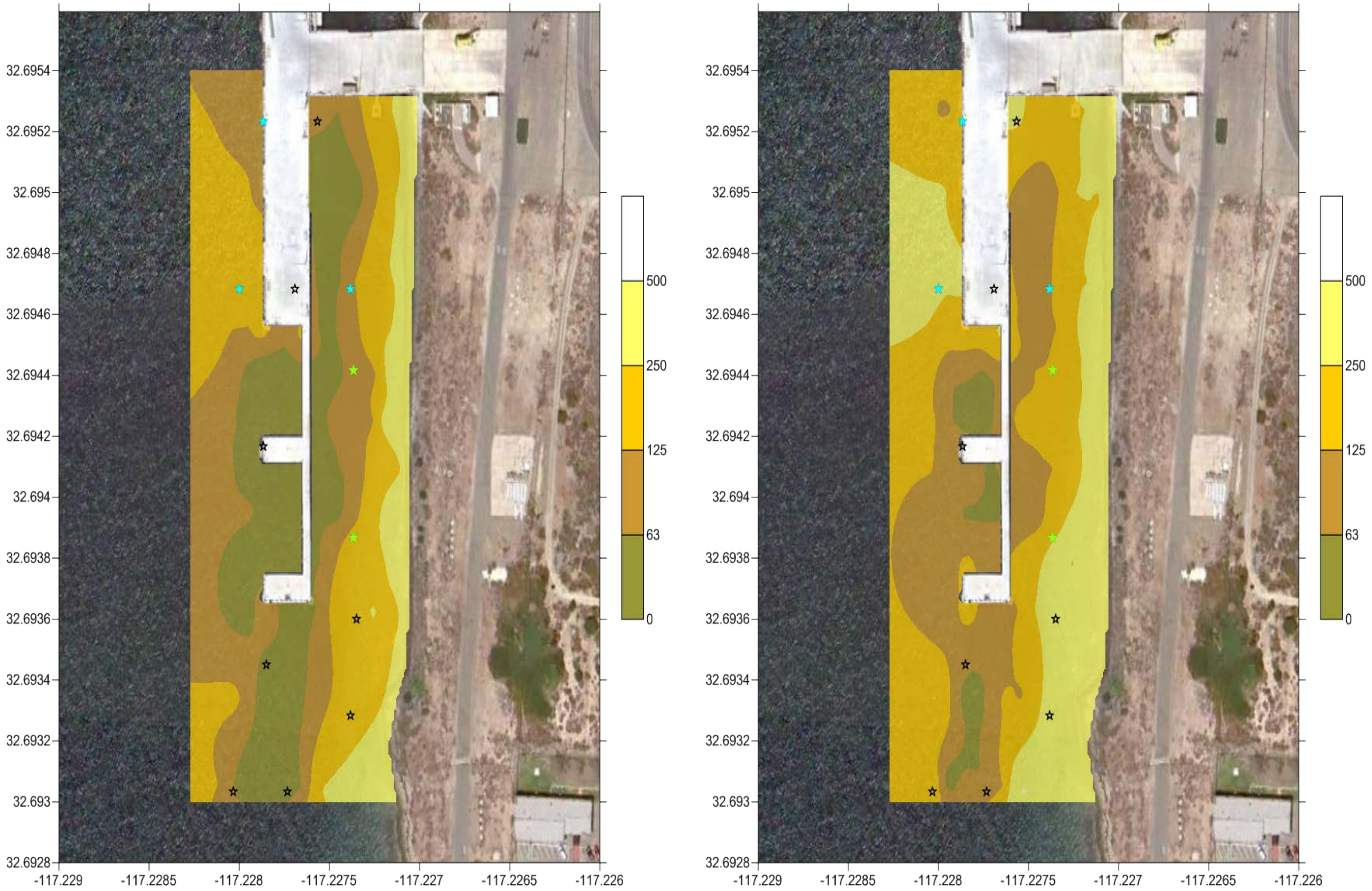

Figure 8. SED-FSP estimated mean particle size map for the 0-6 inch (left) and 6-12 inch (right) depth intervals. Trend of courser to finer materials from the shore to the pier in the surface sediments then courser from pier into Bay. The underlying layer is courser in comparison to the surface layer. Black stars indicate historical sampling locations where no VOCs were detected. Blue stars indicate historical sampling locations where VOCs were detected in deep samples (~5 feet), and green stars indicate historical sampling locations where VOCs were detected in both shallow and deep samples (~ 1 foot and ~5 feet).

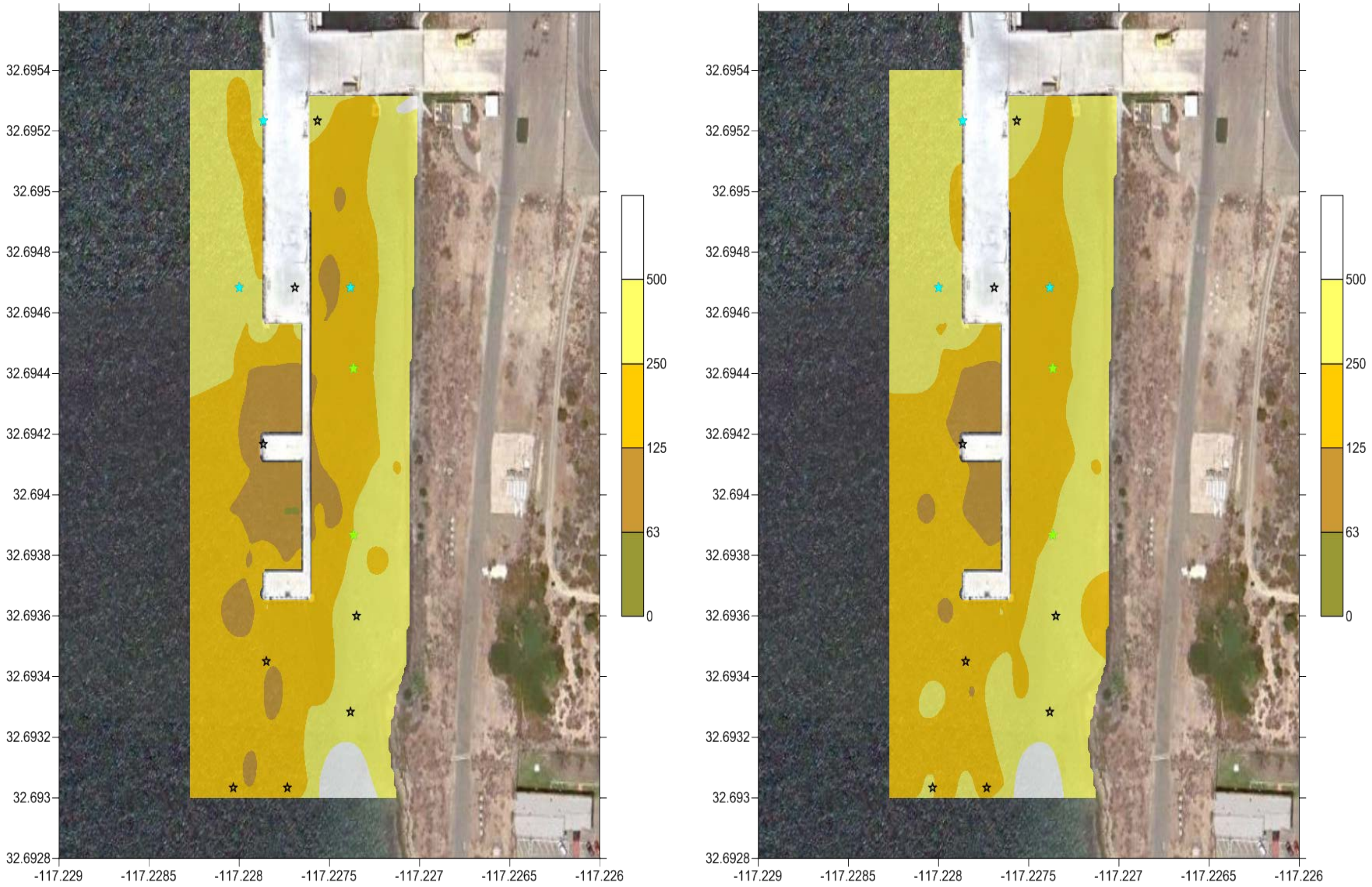

Figure 9. SED-FSP estimated mean particle size map for the 12-18 inch (left) and 18-24 inch (right) depth intervals. Results show courser materials at depth, the VOCs encountered in deeper samples are associated with courser materials. Black outlined stars indicate historical sampling locations where no VOCs were detected. Blue stars indicate historical sampling locations where VOCs were detected in deep samples (~5 feet), and green stars indicate historical sampling locations where VOCs were detected in both shallow and deep samples (~ 1 foot and ~5 feet).

Several patterns and trends are evident from the sediment texture maps. First, there is a pattern of coarser grained materials near the shoreline, progressing offshore to finer materials in the vicinity of the pier finger extending towards the south, transitioning to somewhat coarser material further offshore from the pier. Also, there is a general trend toward coarser materials at depth across the site. Finally, stations where VOCs were detected in the shallow subsurface (~ 1 foot depth) (SPAWAR, 2001) tend to reside at the inshore boundary between the coarser shoreline materials and the finer offshore materials. Stations where VOCs were detected previously only at the deeper horizon (~3 foot depth) tend to align with the coarser materials offshore or at depth. Together, these results suggest that fine grain materials near the pier may be acting to retard the discharge of VOCs in the pier area, and discharge is directed more to the zone inshore of these fine-grained materials or perhaps beneath the fine layer into coarser sediment offshore of the pier.

5.4.3 ANACOSTIA RIVER ACTIVE CAPPING PILOT STUDY SITE, WASHINGTON, D.C.

Anacostia River Thin-Layer Cap Survey Results

The sand cap at the Anacostia River Active Capping Pilot Study was constructed in March 2004 as part of a study characterizing the efficacy of active cap technologies. According to the study site placement plan, the target thickness of the sand cap was 12 inches, a post-placement study conducted soon after installation found the actual thickness to be 8.9 ± 3.2 inches, ranging from 0.25 feet at the edges to 1.25 feet at the south eastern corner (Ocean Surveys, 2004).

A threshold value of SED-FSP response was used to indicate the interface of the cap material and underlying native sediment. The selection was based on observations of SED-FSP responses along the middle transect (locations AR-11, AR-12, AR-13, AR-14), the value selected is approximately at the mid-point between the acoustic responses to cap material and underlying sediment.

The survey results are shown in Figure 10, the colors of the symbols indicating depth horizons of the capping material as measured by the SED-FSP. The figure shows that the cap is greatest in thickness in the eastern corner and generally less on the south western portion. At locations AR-07 and AR-15, cap thickness was measured in the 1 to 5 inch interval, these locations are off the cap target area. Larger particles were not measured at any of the off-cap locations.

The average cap thickness, based on the 12 on-cap deployment locations is 14.3 ± 4.2 inches, within limits of the target thickness of 12 inches.

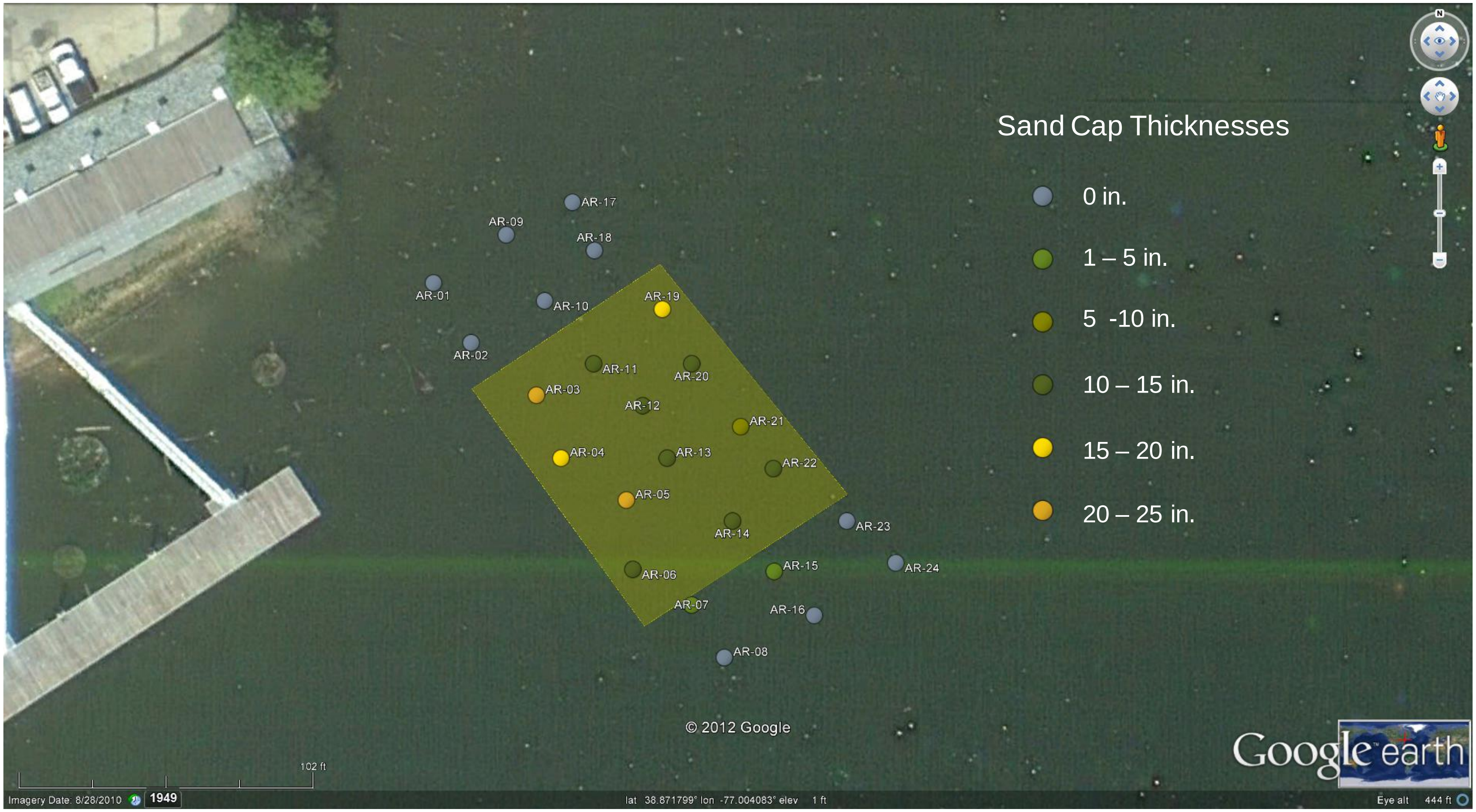

Figure 10. SED-FSP grain size measurements for Anacostia River sand cap survey.
Rectangular area is cap location according to the placement contractor. Symbols represent depth horizons of cap material as measured by the SED-FSP, the legend on the right side of the figure indicate depths of cap material.

5.4.4 GLOBAL APPLICATION OF CALIBRATION PARAMETERS

All SED-FSP responses that were validated by laboratory analysis have been fitted to the data and are accumulated in Figure 11 below. Calibration of the SED-FSP unit is a two-step process; pre-calibration in the laboratory using constructed sediments of known sizes and post-deployment calibration using site sediments. Pre-calibration of the unit prior to deployments is required due to possible changes to SED-FSP responses because of replacement or repositioning of the microphone sensor or the Delrin insulator. The results for the laboratory calibrated SED-FSP across the three application regimes were then combined and an empirically derived power-fit applied to all the data, those results are shown below. For discussion of using an empirically derived power-fit refer to Section 5.4.1 of the Final Technical Report for this project (Chadwick, 2013). The global power fit relationship was used to calculate the performance criteria for this report. The global relationship applied to all the data is the following:

$$\textbf{Mean Grain Size} = 6.114 \times (\textbf{Calibrated-FSP})^{0.861}$$

The consistency of the data across these three demonstrations indicates that this global, empirical calibration may be applicable at other sites at similar levels of reliability, efficiency and specificity as described here. The relationship will continue to be adjusted as necessary and evaluated for subsequent deployments.

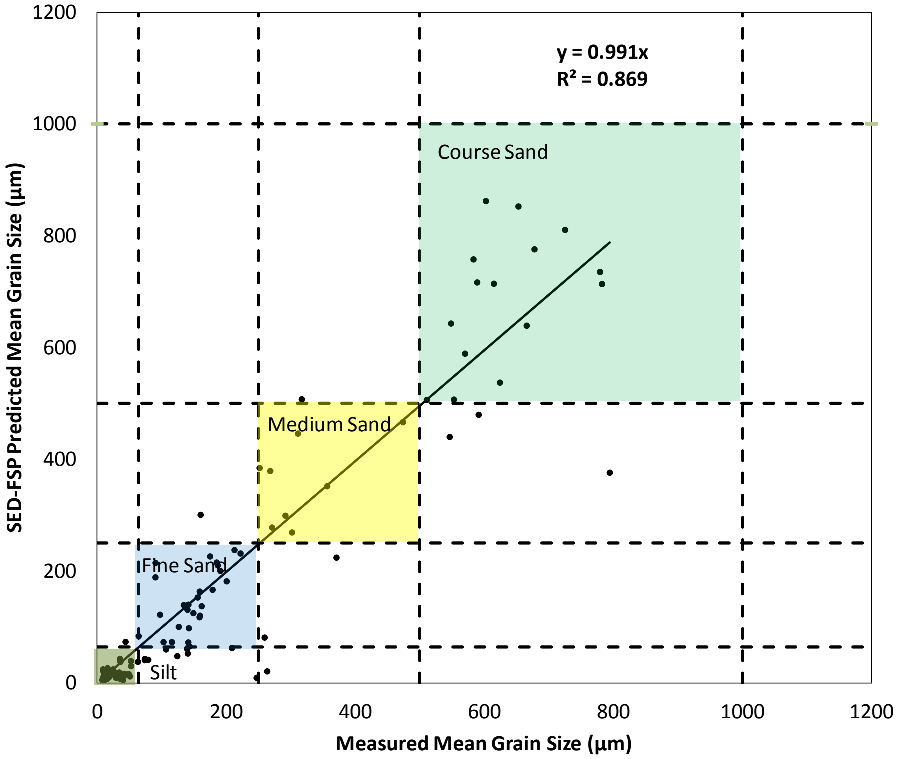

Figure 11. Global SED-FSP calibration – Chollas Creek, IR Site 9 and Anacostia River thin-layer cap deployments.

6.0 PERFORMANCE ASSESSMENT

The project performance objectives were met. The objectives focused on rapid, in situ classification of surface sediment type (quantitative) over a broad range of applications and conditions (qualitative). The quantitative objective was achieved by meeting the stated criteria for the objectives of reliability, efficiency and specificity by corroboration of SED-FSP results with verification analysis of sediments. The qualitative performance assessment was achieved by providing rapid, in situ survey maps delineating areas of significance at the three application regimes.

6.1 PERFORMANCE OBJECTIVES

6.1.1 OBJECTIVE 1: RAPIDLY CLASSIFY SURFACE SUBSTRATES IN SITU

Success was based on meeting criteria to accurately and rapidly measure sediments in situ. The success criteria were defined as:

- Reliability – Measure of the percentage of correctly classified stations in comparison to the total number of stations.
- Efficiency – For each grain size classification (sand, silt, clay), efficiency measures the percentage of correctly classified stations in that level in relation to the total number of stations classified in that level.
- Specificity – Measures percent of correctly classified stations in that level out of the total number of stations actually in that level.

The target goals for reliability, efficiency, and specificity were set at 80%. The summary of the criteria results are shown in Table 4 below, the accumulated results for all measurements are in Appendix A of the Final Technical Report (Chadwick, 2013). Efficiency and reliability are determined for sand and silt grain size classes separately while the reliability criteria is based on all size classifications. Neither the laboratory analyzed samples or the SED-FSP responses yielded clay sized classifications, therefore efficiency and specificity criteria are not reported for clay.

Table 4. Performance criteria surpassed goals for reliability, efficiency and specificity. The table shows number of stations and result percentages.

Target Criteria	Measured Criteria				
	Description			No. Stations	Result
Reliability – 80%	Reliability		Correctly predicted stations	103	92%
			Total stations	112	
Efficiency – 80%	Efficiency	Silt	Correctly predicted silt stations	39	85%
			Total predicted silt stations	46	
		Sand	Correctly predicted sand stations	64	97%
			Total predicted sand stations	66	
Specificity – 80%	Specificity	Silt	Correctly predicted silt stations	39	95%
			Total silt stations (ASTM)	41	
		Sand	Correctly predicted sand stations	64	90%
			Total sand stations (ASTM)	71	

6.1.2 OBJECTIVE 2: DEMONSTRATE APPLICABILITY FOR A RANGE OF APPLICATIONS

Confirmation for this objective was achieved by meeting the stated criteria for rapidly providing survey maps delineating areas of significance at the three application regimes: a GSI site, a contaminated sediment site, and a thin-layer cap. Confirmation of this objective was determined by the investigators through a process of analytical validation, review, comparison to historical studies and best professional judgment. The objective was demonstrated by the ability to:

- Mobilize, operate, and demobilize the equipment;
- Rapidly operate the system in situ;
- Produce spatial maps of surface and sub-surface grain size; and
- Identify potential groundwater discharge zones, areas of high fines associated with contaminated sediments, and extent and depth of a thin-layer sand cap.

7.0 COST ASSESSMENT

7.1 COST REPORTING

The basis for acceptance of the SED-FSP technology is demonstrating that system use offers cost savings relative to obtaining comparable results by traditional or other methods or surveys. The SED-FSP system and its components and implementation are non-complex, therefore calculating costs for comparing to traditional methods of grain size data collection is straightforward. Navigational and equipment handling costs associated with deploying the SED-FSP technology is similar to deployment of grab or core samplers or other field collection techniques. The difference in the technology comparison therefore lies in sediment sample handling and the procedure of grain size measurement. In the case of the SED-FSP, the probe is activated on the sediment bottom and data is acquired then processed and analyzed. In the case of traditional methods, a sample collection device (grab, core sampler) is deployed on the sediment bed, the sample raised to the surface and extracted from the device, the sample is handled (sample container, labels, documentation, custodial management, storage, etc.), the sample is processed (homogenized, extruded), shipped, analyzed (ASTM D422, textural analysis, instrumental method), and reported.

7.2 COST ANALYSIS

7.2.1 COST BASIS

The cost basis for analysis can be taken directly from the demonstration field efforts. The field efforts were real applications of the technology, in the case of the IR Site 9 survey the SED-FSP effort was integrated into a comprehensive feasibility study work plan that was scheduled for Spring 2013 (NAVFAC, 2009). The Chollas Creek demonstration was similar in spatial scope, and of higher resolution, than a previous site characterization study. Scale up in costs would be directly related to the spatial scale and sampling resolution of future applications.

7.2.2 COST DRIVERS

The key cost drivers for application of the SED-FSP system are capital costs, labor, transportation, and those associated with planning, mobilization, demobilization, data analysis and reporting. Capital costs can be easily recaptured based on savings over traditional methods of acquiring grain size surveys of comparable scope and resolution. As field personnel gain knowledge and experience in using the system and other site characterization tools are leveraged (e.g., Trident, UltraSeep), personnel will become more efficient in executing the project.

The main operating costs are associated with the labor costs and number of personnel required for navigation and equipment handling, this ranged widely for the three demonstrations. These were found to be mainly determined by the effort required to navigate to and acquire the station and maintain the location. At IR Site 9, at the mouth of the channel to San Diego Bay, ocean conditions present required at least four experienced boat handling crew to man the deployment vessel (not including the SED-FSP operator). On the other hand, at the slow moving, low-energy Anacostia River location only a single boat operator and a SED-FSP operator were required to complete the task. As stated earlier, the boat handling capabilities are approximately similar regardless if the SED-FSP is deployed or if samples are collected for analysis. Other factors included processing and analyzing data, and writing field, survey and project reports.

System maintenance is minimal because the system is non-complex, but failure or breakage of components would have to be addressed. Replacement parts would be required from the manufacturer, costs would be recouped as savings over the use of traditional grain size survey methods.

7.2.3 LIFE CYCLE COSTS

Estimates of life cycle costs were based on the expected working life of the systems (5-10 years). The current rates indicate that the capital investment for the SED-FSP including ancillary equipment could be recouped within the expected 5-10 year working life with ~30 uses/year, which is well within the expected market demand for the technology (Table 5).

Table 5. Rental Rates for the SED-FSP based on life cycle costs.

Estimate of Initial Cost for Capital and Ancillary Equipment			
Item			Initial Cost
SED-FSP			$5000
Ancillary – Air Compressor/Supply			$500
Ancillary – Field Computer			$500
Ancillary – Drive System			$4000
Total SED-FSP			**$10,000**
Equipment Replacement Cost Estimate			
Inflation Rate	4%		
	Years of Use		
	0	5	10
SED-FSP & Ancillary Replacement	$10,000	$12,000	$14,000
Estimated Rental Rate Including Inflation and Maintenance			
Maintenance Rate	5%		
SED-FSP & Ancillary	Uses/Year	Years of Use	
		5	10
	10	$252	$147
	20	$126	$74
	30	$84	$49
	40	$63	$37
	50	$50	$29
Estimated Rental Rates (per/day)			
SED-FSP			$50
Ancillary – Air Compressor/Supply			$25
Ancillary – Field Computer			$25
Ancillary – Drive System			$50
Total SED-FSP			**$150**

7.3 COST COMPARISON

The cost comparison of a hypothetical grain size survey using the SED-FSP technology and a survey based on sample collection and grain size determination by traditional and other methods is described in Table 6 below. Excluded in the costs are travel, shipping, and boat and crew costs. It’s assumed that these would be very similar for SED-FSP and field efforts using traditional sampling equipment (e.g., sediment corer), the SED-FSP footprint and weight is similar to standard sampling devices therefore boat and equipment handling requirements would be similar. The surveys depicted in Table 6 are for 2 days for acquisition of 32 stations. The estimates assume that a single station is acquired every 30 minutes in an 8 hour day for both the SED-FSP and the sediment sampling method. In the case of the SED-FSP, this is a very conservative estimate; during actual usage the on-station duration was often as short as 10 minutes but averaged 15 to 20 minutes, even with collection of validation samples by a diver. Thirty minutes per sample for a traditional sediment sampler may be an underestimate of the actual time needed. Based on actual experience, a sediment sampler requires recovering the sampler to the deck of the vessel (not necessary with the SED-FSP), unloading of the sediment sample, decontamination if required, loading of the sampler with containers, and on-board processing (core extrusion, mixing, etc.).

The SED-FSP survey estimate also includes sample collection at 25% of the total stations for collection of site validation samples. The 25% estimate was based on the actual validation sampling performed during the demonstration field efforts. At Chollas Creek 100% of the stations were sampled for validation; at IR Site 9, 23% of stations were sampled; and at the Anacostia River location 25% of the stations were sampled. The need for and the number of samples required for site-specific validation is important because it can substantially increase costs as is evidenced in the table below. As the technology and its use matures and/or techniques are developed and acquired that address calibration of the unit, the need for site-specific and validation samples may be reduced or even eliminated.

The labor costs for SED-FSP operation and deployment of traditional sampling equipment are nearly the same, \$11,280 for SED-FSP compared to sampling costs of \$11,050. The differences in the non-labor costs are substantial, due primarily to differences in the number of samples submitted for validation analysis. In the bottom part of Table 6 below (“Analytical” section), costs are presented for four other methods of grain size analysis: traditional sieving and sedimentation (ASTM D422), laser diffraction, electro-zone sensing, and microscopy. The number of samples submitted for analysis by traditional (or other) methods are 32, the number submitted for SED-FSP validation are 8, this difference influences the overall project costs (bottom of Table 6) the most substantially.

A simplified sieving technique to determine size texture (e.g., 2 millimeter [mm] and 63 micromole [µm] sieves) was also considered, representing the most rudimentary technique of textural grain size analysis that would yield the basic Wentworth classifications. But the effort is non-trivial; hardware preparation is required, sieving is time consuming as would be sample handling and drying of samples, quantification and documentation. It was estimated that the cost of the ASTM D422 method closely represents the cost of a basic sieving technique.

Table 6. Cost comparison of a survey for grain size using SED-FSP system and traditional sediment sample collection and analysis by standard method.

Cost Category	**Description**	**SED-FSP**			**Alternate (inc./sampling)**			**Comments**
	Labor Cost	*Rate*	*Hours*	*Cost*	*Rate*	*Hours*	*Cost*	
Mobilization	Calibration	$120	6	$720	$120	0	-	
	Checks/preparation	$120	8	$960	$120	8	$960	
	Packing	$65	4	$260	$65	8	$520	
	Shipping	$65	2	$130	$65	2	$130	
	Sub-total			**$2070**			**$1610**	
SED-FSP Operation	On-site setup/testing	$120	4	$480	$120	0	-	
	Equipment handling	$65	16	$1040	$65	0	-	
	Operator/user	$120	16	$1920	$120	0	-	
	Data processing	$120	4	$480	$120	0	-	
	Sub-total			**$3920**			**-**	
Sediment Sampler Operation	On-site setup/testing	$120	4	$480	$120	4	$480	SED-FSP sediment validation costs for sample collection at 25% of total locations.
	Equipment handling	$65	6	$390	$65	24	$1560	
	Operator/user	$120	4	$480	$120	16	$1920	
	Sub-total			**$1350**			**$3960**	
Sample Processing	Handling	$65	4	$260	$65	16	$1040	SED-FSP sediment validation costs for sample collection at 25% of total locations.
	Processing/preparation	$65	2	$130	$65	8	$520	
	Custody/management	$120	2	$240	$120	4	$480	
	Shipping	$65	2	$130	$65	4	$260	
	Sub-total			**$760**			**$2300**	
Demobilization	Cleaning/breakdown	$120	4	$480	$120	4	$480	
	Packing	$65	8	$520	$65	8	$520	
	Shipping	$65	4	$260	$65	4	$260	
	Sub-total			**$1260**			**$1260**	
Reporting	Reporting	$120	16	$1920	$120	16	$1920	
	Sub-total			**$1920**			**$1920**	
	Total Labor Costs			**$11,280**			**$11,050**	

Table 6. Cost comparison of a survey for grain size using SED-FSP system and traditional sediment sample collection and analysis by standard method (continued).

Cost Category	Description	SED-FSP			Alternate (inc./sampling)			Comments
	Labor Cost	*Rate*	*Units*	*Cost*	*Rate*	*Units*	*Cost*	
Materials Costs	Core liners	$25	8	$200	$25	32	$800	SED-FSP sediment validation costs for sample collection at 25% of total locations.
	Sample containers	$5	8	$40	$5	32	$160	
	Cleaning supplies	$25	1	$25	$25	4	$100	
	Shipping supplies	$25	1	$25	$25	4	$100	
	Other misc.	$25	1	$25	$25	4	$100	
	Sub-total			**$315**			**$1260**	
Analytical	ASTM D422	$100	8	$800	$100	32	$3200	Documented costs.
	Laser diffraction (Malvern, Horiba)	$115	8	$920	$115	32	$3680	Historical costs.
	Electrozone sensing (Coulter counter)	$150	8	$1200	$150	32	$4800	Discussion with laboratory representative.
	Microscopy	$200	8	$1600	$200	32	$6400	Estimation
Project Cost	ASTM D422			$12,395			$15,510	Totals according to analytical methods for 2-day survey, 32 surface sediments collected and analyzed.
	Laser diffraction			$12,515			$15,990	
	Electrozone sensing			$12,795			$17,110	
	Microscopy			$13,195			$18,710	

Table 7 below is a comparison of project costs excluding the analytical costs associated with site-specific calibration of the SED-FSP. The table reveals that validation sampling and analysis adds substantially to the overall costs of a SED-FSP deployment, there would be substantial cost advantages gained by reducing or eliminated this requirement. This may be accomplished as the technology matures and experience is gained through its continued use.

Not addressed in the cost evaluation is that the hypothetical survey represents a surface characterization study only, not capturing the effectiveness of the technology for acquiring a three-dimensional survey map. Adjusting to account for the vertical dimension, accomplished by coring and sectioning, would result in substantial increases in analytical costs.

Table 7. Cost comparison of a survey for grain size using SED-FSP system and traditional sediment sample collection and analysis by standard method.

Cost	Description	SED-FSP	Traditional	Comments
Project Cost	ASTM D422	$9170	$15,510	Totals according to analytical methods for 2-day survey. 32 surface sediments collected and analyzed.
	Laser Diffraction	$9170	$15,990	
	Electrozone Sensing	$9170	$17,110	
	Microscopy	$9170	$18,710	

8.0 IMPLEMENTATION ISSUES

8.1 COST OBSERVATIONS

The capital costs for the technology would be expected to be recovered quickly as they are low. The key cost drivers are labor, deployment costs, transportation/shipping, and capital equipment costs. The costs are the standard costs that are normally associated with sediment sampling field deployments.

8.2 PERFORMANCE OBSERVATIONS

The field unit performed in accordance with laboratory observations of the developmental unit. Deviations from performance objectives occurred when sampling near shore at NASNI IR Site 9 into unsaturated sediment and on the sand cap where strong vertical gradients made it difficult to match SED-FSP profiles with samples near the sand/native sediment interface. The SED-FSP was capable of identifying the interface at the sand/native sediment types but care should be employed where these types of situations may occur.

8.3 SCALE UP

The demonstrations were performed at full-scale, scale up of this technology will not be a factor. The demonstrations at NBSD Chollas Creek and NASNI IR Site 9 are known to the investigators to be representative of sites where the technology benefits can be employed. The thin layer cap on the Anacostia River was installed as a study site and as such is small compared to actual applications of contaminated sediment caps. Nevertheless, sufficient grain size profiles were taken from the Anacostia site to demonstrate the technology.

8.4 LESSONS LEARNED

Several important lessons were learned during the progression of the demonstrations. Subsurface obstructions impose severe risks of breakage of the probe. This occurred at the IR Site 9 location and caused the survey to be delayed a week. Use of a video monitoring system is critical and should not be overlooked. In addition, the need for calibration of the unit with site specific sediments wasn't expected. Application of the global calibration parameters will be monitored as the technology matures. Of potential interest is the development of an alternate method of pre-deployment calibration, whether through use of the "known" sediments or by application of an alternate noise source to the probe tip.

During the field deployments, mean grain sizes measuring in the clay range (< 3.9 µm) were not acquired either as a result of SED-FSP response or as results of laboratory analysis of site samples from any of the demonstration activities. Laboratory testing also showed that the SED-FSP did not resolve or accurately predict sizes of this range and smaller. While the system correctly differentiates between fine and sand mean sizes and responds accurately to sand sub-classifications, the unit should be considered for use where differentiation of sand and fines are required. Differentiation of silty (3.9 - 63 µm) and clay sizes was not validated.

8.5 END-USER ISSUES

The technology was deployed at the IR Site 9 location and the data will provide ancillary support to the broad FS that will occur there. The technology has also been selected to be deployed at Marine Corps Base Quantico, where a thin-layer cap is scheduled to be installed. The SED-FSP will be used to verify placement of the cap.

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APPENDIX A

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