JOINT TRANSPORTATION RESEARCH PROGRAM

FHWA/IN/JTRP-2009/21

Final Report

**A TRUCK-MOUNTED SCOUR INSPECTION
SYSTEM FOR INDOT**

**Dennis Lyn
Thomas Cooper
Ranadeep Das**

March 2010

INDOT Research

TECHNICAL *Summary*

Technology Transfer and Project Implementation Information

TRB Subject Code: 22-7 River and Stream Mechanics
Publication No. FHWA/IN/JTRP-2009/21, SPR-2933

March 2010
Final Report

A Truck-Mounted Scour Inspection System for INDOT

Introduction

Scour monitoring may be a useful tool for INDOT in dealing with local scour problems at bridge sites, and a truck-mounted scour-monitoring system is an attractive option offering flexibility in deployment and cost-effectiveness. This work builds on the results of previous NCHRP project (21-07) which initially developed such a system. In particular, two aspects related to the further development of such a system are considered: i) a web application

that combines the latest available information regarding streamflow with relevant information regarding bridges considered susceptible to bridge scour, thereby assisting in truck-deployment decisions, and ii) development of an acoustic positioning system as a replacement of the original mechanical positioning in order to improve the ease of use.

Findings

A web application has been developed in Macromedia (now Adobe) Flash 7, supplemented by Perl programs running in a UNIX environment, that takes as input hourly USGS stream gaging data, and displays these graphically on a map, together with relevant information about scour-critical bridges. This should provide decision makers the latest available information to deploy a truck-mounted scour-monitoring system in an effective manner.

An acoustic positioning system, based on acoustically measuring distances from transmitters attached to the scour sonar housing to an array of receivers of known fixed positions, is intended to provide a more robust and easier-to-use means of determining the position of the sonar

scour monitor than in the original system. Laboratory tests were performed with the system in isolation, and results were compared with locations determined from a Total station. It was found that, under relatively ideal laboratory conditions, the system could locate the transmitters within 1-ft in the horizontal and 1-ft in the vertical. For the more demanding location of a probed point on a hypothetical streambed, the system errors often exceeded this specification. Field tests, undertaken for both stationary-truck and moving-truck applications, but with the positions of transmitters nominally fixed with respect to the receivers, showed that the results were noisier, but appropriate pre-screening and post-processing yielded useful data.

Implementation

The web site has been continuously functioning for over four months with only a single interruption of service for more than a few hours.

Further field testing will likely be performed by INDOT Office of Research and Development before the system can be adopted for routine use.

Contacts

For more information:

Prof. Dennis Lyn

Principal Investigator
School of Civil Engineering
Purdue University
West Lafayette IN 47907
Phone: (765) 494-9615
Fax: (765) 494-0395
E-mail: lyn@purdue.edu

Indiana Department of Transportation

Office of Research and Development
1205 Montgomery Street
P.O. Box 2279
West Lafayette, IN 47906
Phone: (765) 463-1521
Fax: (765) 497-1665

Purdue University

Joint Transportation Research Program
School of Civil Engineering
West Lafayette, IN 47907-1284
Phone: (765) 494-9310
Fax: (765) 496-7996
E-mail: jtrp@ecn.purdue.edu
<http://www.purdue.edu/jtrp>

Final Report

FHWA/IN/JTRP-2009/21

A TRUCK-MOUNTED SCOUR INSPECTION SYSTEM FOR INDOT

By

Dennis Lyn
Professor

Thomas Cooper
Hydraulics Laboratory Manager

Ranadeep Das
Graduate Research Assistant

School of Civil Engineering
Purdue University

Joint Transportation Research Program
Project No. C-36-32Q
File No. 9-8-17
SPR-2933

Conducted in Cooperation with the
Indiana Department of Transportation and the
Federal Highway Administration
U.S. Department of Transportation

The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Indiana Department of Transportation and Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

Purdue University
West Lafayette, Indiana
March 2010

1. Report No. FHWA/IN/JTRP-2009/21	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle A Truck-Mounted Scour Inspection System for INDOT		5. Report Date March 2010	
		6. Performing Organization Code	
7. Author(s) Dennis Lyn, Thomas Cooper, and Randeep Das		8. Performing Organization Report No. FHWA/IN/JTRP-2009/21	
9. Performing Organization Name and Address Joint Transportation Research Program 550 Stadium Mall Drive Purdue University West Lafayette, IN 47907-2051		10. Work Unit No.	
		11. Contract or Grant No. SPR-2933	
12. Sponsoring Agency Name and Address Indiana Department of Transportation State Office Building 100 North Senate Avenue Indianapolis, IN 46204		13. Type of Report and Period Covered Final Report	
		14. Sponsoring Agency Code	
15. Supplementary Notes Prepared in cooperation with the Indiana Department of Transportation and Federal Highway Administration.			
16. Abstract <p>Scour monitoring may be a useful tool for INDOT in dealing with local scour problems at bridge sites, and a truck-mounted scour-monitoring system is an attractive option offering flexibility in deployment and cost-effectiveness. This report deals with two aspects related to the further development of such a system: i) a web application that combines the latest available information regarding streamflow with relevant information regarding bridges considered susceptible to bridge scour, thereby assisting in truck-deployment decisions, and ii) development of an acoustic positioning system as a replacement of the original mechanical positioning in order to improve the ease of use.</p> <p>The web application, written in Macromedia (now Adobe) Flash 7, provides a graphical (map) display of stream gaging sites and bridges, and the relevant information. The report discusses briefly its use and the software implementation.</p> <p>The acoustic positioning system is based on acoustically measuring distances from transmitters attached to the scour sonar housing to an array of receivers of known fixed positions, and is intended for use in determining reproducibly the position being probed by a scour sonar. Laboratory tests were performed with the system in isolation, and results were compared with locations determined from a Total station. It was found that, under relatively ideal laboratory conditions, the system could locate the transmitters within 1-ft in the horizontal and 1-ft in the vertical. For the more demanding location of a probed point on a hypothetical streambed, the system errors often exceeded this specification. Field tests, undertaken for both stationary-truck and moving-truck applications, but with the positions of transmitters nominally fixed with respect to the receivers, showed that the results were noisier, but appropriate pre-screening and post-processing yielded useful data.</p>			
17. Key Words Scour, bridges, monitoring, acoustic positioning.		18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 56	22. Price

Table of Contents

1.	Introduction	1
2.	The Web application	2
2.1.	Introduction.....	2
2.2.	Description of Web Page and its use.....	2
2.3.	Details of web application program design.....	4
2.4.	Changing the display program or its input	6
2.4.1.	Changes made to the display program by the PI	7
2.5.	Stream gaging data transfer and conversion	7
2.6.	Summary	9
3.	The truck-mounted scour-monitoring system	10
3.1.	Background.....	10
3.1.1.	The NCHRP truck.....	10
3.1.2.	The wireless sonar sounding assembly.....	11
3.1.3.	The ultrasonic stage sensor	12
3.1.4.	The truck position sensor	12
3.1.5.	The ETI electronics and data acquisition	12
3.2.	The acoustic (HEXAMITE) positioning system	13
3.2.1.	Background	13
3.2.2.	Conceptual basis of an acoustic positioning system.....	14
3.2.3.	Implementation of an acoustic positioning system.....	14
3.3.	Summary	17
4.	Testing of the positioning system.....	18
4.1.	Laboratory testing	18
4.2.	Field testing of the HEXAMITE positioning system	22
4.2.1.	Results from field testing I: Stationary-truck tests	23
4.2.2.	Results from field testing II: Moving-truck tests.....	27
4.3.	Further observations and concerns	31
4.4.	Summary	31
5.	Summary and implementation plans	33
5.1.	The positioning system.....	33
5.2.	The web application	33
5.3.	Plans for implementation.....	33
5.3.1.	Web application	33

5.3.2. Truck-mounted scour-monitoring system	33
6. References	35

Appendices

A. Assembling the system	37
A.1. The crane-mounted electronics enclosure box, the sonar, and the acoustic transmitters	37
A.1. The measurement wheel.....	39
A.2. The receiver array.....	39
A.3. The data acquisition computer	40
B. Using the data acquisition software	42
B.1. Preliminary steps to data acquisition	42
B.2. The data acquisition step: Test and Record modes	43
B.3. Graphical analysis of results	45
B.4. Further comments.....	45
C. Details of the Scour-Monitoring Visual Basic program.....	50
C.1. Calibration of the HEXAMITE system	50
C.2. Temperature-calibration equation and determining distances.....	50
C.3. Determining transmitter coordinates	50
C.4. Determining the coordinates of the probed point on the streambed	51
C.5. Data screening and filtering	51
D. Additional details of the Web Application software	53
D.1. Routines for XML conversion	53
D.2. Routines for data display and web interface	54

1. Introduction

Scour monitoring is considered a useful tool in dealing with the problem of scour at bridge sites, and the search for a flexible and cost-effective approach to scour monitoring led to recent NCHRP projects studying various approaches. A truck-mounted scour-monitoring system is attractive from different perspectives. It can be deployed at different structures (piers, abutments) at the same site, or at different sites entirely. Thus, its benefits can be distributed over a much broader region which will offset its high initial costs. It can provide streambed profile information at a level of detail that is currently unavailable, which might be useful in emergency or near-emergency situations. Moreover, it can also supplement routine inspections, providing data at intervals more frequent than is currently available, and thereby aid in planning and operations.

The present project was undertaken with two main tasks: i) the refinement of a truck-mounted scour-monitoring system, initially developed during NCHRP project 21-07 (Schall and Price, 2004), so as to make its use more straightforward and robust, and ii) the development of software providing almost real-time information regarding flows in streams as well as relevant information regarding bridges that would be available over the Internet, so as to aid in decisions about truck deployment.

Chapter 2 describes the Internet application, most of which was developed by a group under the supervision of Bob McCulloch, its features, and its use. Because the graphical user interface was designed for ease of use, it is relatively intuitive, and so an extended description of its use is not necessary. It is recommended that the user simply access the specified web site and immediately use the web application, using the material in Chapter 2 as a reference. Chapter 2 does also provide some details of the software implementation to guide future modifications or revisions of the software.

Most of this report will be devoted to the further development and testing of the truck-mounted scour-monitoring system. This is divided into hardware and software aspects, i) an acoustic positioning system to track the movement of the articulated crane, used to deploy the scour sonar, and ii) the development of easy-to-use data acquisition software that would assist the operator in the use of the hardware. Chapter 3, while describing the entire (hardware) system, focuses on the new acoustic positioning system. Testing of the system in the laboratory and in the field is reported in Chapter 4. A guide to assembling the hardware on site and the use of the data acquisition software, together with details of the computations done in the software, are given in the appendices.

2. The Web application

2.1. Introduction

The web application is intended as a decision-support tool to enhance the effective deployment of the scour-monitor truck. It does so by providing up-to-date information regarding flow characteristics (stage or discharge or both) of Indiana streams together with relevant information regarding scour-critical bridges in an easy-to-grasp (hence visual) spatial setting. INDOT databases are combined with continuous-feed USGS stream-gaging data, with the final display in a GIS framework. The initial coding was done by Jeremy White and Wonjin Kang, under the supervision of Bob McCulloch. For various reasons, including lack of funding, some final revisions had to be made by the principal investigator (Dennis Lyn). The following describes the main programs involved and discusses the use, the features, and limitations of the web application.

The basic task of the application was divided into two main subtasks, namely, i) the graphical display of the data, and ii) the handling of dynamic (updating) data. As such, program development was carried out separately on each of these subtasks. The graphical display program was largely the work of Jeremy White, and was developed using Macromedia (now Adobe) Flash 7. The result as of this writing can be found at <http://engr.purdue.edu/CEScour/floodindot.html>. By design, the graphical interface is intended to be intuitive, such that it can be used without any significant training. Below, a brief description of its features is given, and is followed by a more detailed discussion of the program elements and limitations. In the current application, the only dynamic data used are the stream-gage data provided by the USGS for approximately 140 stations in Indiana. The second subtask was concerned with the periodic (every hour) data transfer from the USGS source, and then a conversion of the USGS-formatted data into a format that could be used by the graphical display program. Below an outline of the conversion program is also given.

2.2. Description of Web Page and its use

The default web page is shown in Fig. 2.1. The main element is a zoomable, scrollable map of Indiana on which the locations of USGS gaging stations are shown. Depending on the stream stage (water surface elevation) relative to flood stage, the stations are represented by different symbols, as indicated by the legend at the bottom right of the page. For example, if the stream stage is above flood stage as defined by the National Oceanographic and Atmospheric Agency (NOAA), the station is shown as a blinking red triangle (with an exclamation point inside), while if the stream stage is substantially below flood stage, it is shown as a yellow-filled circle. Intermediate stages are shown as blue, yellow, and orange triangles. In Fig. 2.1, several streams above flood stage can be seen along the lower Wabash River. A few locations can be seen represented by a question mark – these indicate stations that are defined to the program but for which no data is available.

When the cursor is placed over a stream gage location, stage data are displayed in a plot of stage vs time in a pop-up form as well as in a somewhat larger format to the right, with also a plot of discharge vs time if discharge data are available (Fig. 2.2). In the pop-up, the USGS station number and name, together with the latest (current) stream stage and flood stage (if available) and date, are also shown. The pop-ups can be 'disabled' by checking the appropriate box at the bottom; in this case, the graph is not shown, but the station information is still displayed. The graphs are however still shown

Fig. 2.1: Web application page, with map of Indiana, including USGS stream gaging stations, variously depicted depending on the relation of actual stream stage to NOAA defined flood stage

to the right, and in addition if stream stage is near or above flood stage, the stage graph to the right will show the region above flood stage in hatching. Although it is expected that the user will usually use the cursor to find the stream-gaging station of interest, it is also possible to find the station by name. Above the graphs to the right is a scrollable list of all the stations defined in the program, with the same color coding as the triangles on the map, e.g., red for stations above flood stage. When a station is selected by the user (by clicking on the name), not only do the graphs show the data for the station, but a ripple effect is generated emanating from the station on the map, thus locating the station on the map.

The other main information provided by the application concerns the locations of the bridges that have been denoted as scour-critical in the INDOT database. This database is treated as relatively static, i.e., the information therein will not change frequently. Scour-critical bridges may be brought up by checking the appropriate box at the bottom. Fig. 2.3 shows the location of the bridges as purple-filled circles. When the cursor is placed on a specific bridge location, information regarding the bridge is provided on the right, including the formal bridge identifier, the district code, the facility carried, the feature (stream) intersected, the number of piers in water, the largest vertical distance (if available), and the scour rating. Such information was thought to be most relevant in deciding on a deployment of the scour truck.

Fig. 2.2: Web page application with cursor placed on a specific gaging station (Wabash River at Covington), showing pop-up window on map (note that the Disable pop-up graph box at bottom is not checked), as well as larger format graph of stage and discharge to the right. On the stage graph, the entire region is shown hatched as the stage is above the NOAA flood stage (defined on the pop-up graph as being 16 ft).

Other spatial data provided by checking the appropriate box are the district and watershed boundaries, a more detailed stream network, and the road network.

A further capability of the application that may be of some interest is the examination of archived data. The default stream-gage data displayed are the most current available (typically the most recent 24-hr period), but if archived data are available, they can be loaded by selecting a date using the drop-down lists at the top right, and clicking on the LOAD button. For the current version of the application, the earliest data available are from 3/17/2009.

2.3. Details of web application program design

The display program requires as input the relatively static information regarding scour-critical bridges and the NOAA defined floodstages of Indiana streams (not all streams have a NOAA defined floodstage), and the dynamic hourly updated information regarding streamflows. All are assumed to be

Fig. 2.3 Web page shown with scour-critical bridges (purple-filled circles), and with the cursor over a specific bridge, the corresponding data of which is shown to the right.

in XML format. The bridge data is currently stored in a file named `myscour.xml`, the floodstage data in `floodpointers.xml`, while the streamflow data are found in separate directories (folders) with the same name, `mastermerge.xml`.

There are currently 203 scour-critical bridges defined in the program, based on data from INDOT MS Access databases. As of this writing, the database specifying the scour-critical bridges is dated as being created Jan. 11, 2005, and so is likely in need of updating. Issues specifically related to updating are dealt with in a separate section below. Scour-critical bridges are taken to be those in the INDOT database with a scour rating of 3 or less. The information provided for each bridge is taken from the "Location" sheet, and was chosen based on potential relevance to the deployment of the scour truck. It should be noted that the terminology and conventions of the INDOT database are adopted. For example, facility carried refers to the route (highway) name, and the features intersected refer to the name of the stream below the bridge. Similarly, in the specification of the "Largest vert. distance", the value is given in ft multiplied by a factor of 10, e.g., a value of 0116 would refer to a distance of 11.6 ft. Other information, if desired, could also be displayed by a relatively straightforward modification of the code, provided that it is available in the database (not all data is available for all bridges).

There are currently 145 USGS stream gaging stations defined in the program, these being determined by the USGS personnel (Mark Hopkins) involved in the programming when the program was first developed (ca. 2005). Because new stations may have been added and possibly some may have discontinued operation, to the USGS network since that time, not all current USGS stations are necessarily included. Of the 145, two stations are defined in terms of being represented on the map, but have no information (e.g., name, identification number) associated with them. On the map, they are represented by question marks. Comparison with the USGS map suggest that they correspond to the stations 04099510 (Pigeon Creek near Angola) and 04101370 (Juday Creek near South Bend), both currently reporting data on the USGS web site. Two other stations defined and associated with names and identification numbers seem to be chronically without stream data, namely 03376350 (S. Fork Patoka near Spurgeon) and 04177810 (Fish Creek near Artic). Neither appear on the current USGS web site map, and so may no longer be operating. New stream datafiles are uploaded every hour, but not all sites will have a new datafile every hour; if there is no new datafile associated with a station, it will appear on the Current Data map with a question mark. As a result, a few stations will sporadically appear as a question mark.

Even though new datafiles may be available every hour for a given site, this does not mean that the information is necessarily updated every hour. Most station data are updated every hour, but a number of stations have much shorter update intervals, some as short as every 10 minutes. On the map, every data point is plotted, and so those with shorter update intervals will have more points. Different stations may also have different lag times in reporting, i.e., the difference between the current time and the time of the most recent data. At a handful of stations, the lag is less than 90 minutes, or may exceed 6 hours, but at most stations the lag times will lie between two to five hours. Familiarity with the flow patterns (here the watershed layer can be useful) may aid in qualitative predictions of flooding, in that widespread flooding in the upstream regions of a watershed will often lead to eventual flooding in the downstream regions.

While all operating sites will have stage (water surface elevation) information, fewer will have discharge information. As a result, the discharge graph to the right may be empty. If there is discharge information available at a station, it will generally track the stage data closely, with the same trends. From this point of view, the discharge data may be considered somewhat redundant. In most cases, discharge data will be updated at the same time as the stage data, such that the two data streams are synchronized; in rare cases, it may happen that the two datastreams may sporadically be updated at different times.

2.4. Changing the display program or its input

While the display program was designed to deal with the dynamic stream gaging data in mind, it assumes that the reporting stations and the scour-critical bridges would be relatively static, i.e., changes would be relatively infrequent and modest. As a result, changing the reporting stations or the scour-critical bridges on the map is a somewhat cumbersome process. All of the 'live' symbols for the gaging stations and bridges were placed manually and numbered sequentially. Adding new gaging stations or scour-critical bridges would therefore be done in the same way, and hence would require changing the code, and not just the input datafiles. Deleting stations or bridges would in comparison likely be simpler in that it would only require rendering the already available symbols invisible and cancelling any associated actions, but this would still require code changes. Additional details of the Web application display code are given in Appendix as an aid to changing the code.

Adding stations or bridges would require changes also in the input datafiles. The XML datafiles require that all defined stations or bridges be included in the datafiles, in the sequential order defined in

the program, even if no useful data is associated with the station or bridge. Again, even if it is desired to delete stations or bridges, it is recommended that this be done by making changes only in the display program. Note that if entries in the XML datafiles are deleted, then correct functioning of the display program will require changes in the display program.

2.4.1. Changes made to the display program by the Principal Investigator

The earliest version of the application was made available on the Internet in early 2006, but there were several unresolved issues. The most important was that the streamflow data transfer tended to be unstable, with the result that the application was frequently not updating. To make matters worse, because the date of the displayed data was not provided, the user could be easily misled into thinking that the displayed data was up-to-date, but in fact may have been months (or possibly years) out of date. A second problem was that the locations of the bridge sites were not consistent with that found in INDOT GIS files. A third more minor issue is that the bridge information displayed in the original program was rather limited. Because no further funding was available for the group under Bob McCulloch to resolve these issues, these had to be dealt with by the principal investigator (Dennis Lyn) as follows:

1. Additional information was placed on the pop-up window, and the graphs. In particular, the date of the most current stream gaging data is included in both pop-up window and graphs. With the date of the displayed data always shown, it is immediately clear to the viewer whether the data being displayed is out of date or not. Similarly, the station name was added to the graph to the right. Previously, the graphs on the right showed the data from the station that was last queried (either by using the cursor on the map or by selecting from the list of stations), and these results remained even if the cursor was moved from the graph (and therefore not operative). Without a station name, it was not immediately clear which station's results were being displayed unless a station was being queried using the cursor. Both of these changes required changes in the code as well as in the input datafiles.
2. An indexing error that caused incorrect referencing of bridges was found and corrected. This required only minor changes to the code.
3. Additional information regarding the scour-critical bridges was provided. This required minor code changes together with a regeneration of the bridge XML datafile.

2.5. Stream gaging data transfer and conversion

The stream gaging data are provided every hour by the USGS. They consist of two types of datafile, one for the stage data with extension .GH, the other for the discharge data with extension, .D. Each reporting station will be represented by one or both files. Each file contains the most recently available data for the quantity (stage or discharge) for approximately the last 24 hours.

The original program for dealing with the stream gaging data was developed by Wonjin Kang under the supervision of Bob McCulloch for a Microsoft Windows environment using Visual Basic. It accessed the USGS server periodically, transferred the appropriate files, extracted the desired information, and created the necessary XML files that were needed as input to the display program. As noted above, difficulties were encountered in the use of this program in that the data transfer step was frequently not successfully completed, with the result that the display program was frequently not provided with any updated data. The exact nature of the data transfer problem was not identified, but it was surmised that an unstable FTP connection contributed to the problem.

After discussion with USGS personnel (Mark Hopkins), it was decided that a more robust approach would rely on a USGS program to perform the data transfer, and hence only data conversion

need to be performed by the project program. As of this writing, the data transfer has been operating continuously since March 2009, with only a single failure lasting more than a day, and this was due to a problem with the USGS code.

The web application is currently being hosted on a UNIX server, and it was convenient therefore to have all programs run within a UNIX environment. The USGS datafiles are transferred to the same server, and so it was decided that the program(s) converting the USGS data to XML input files would also run on the same server. As a result, the original WINDOWS program could not be used, and new programs had to be written.

Aside from the distinction between stage and discharge input files, another distinction between input files may be made, namely that between current data and archived data. It is recalled that the display program is capable of retrieving daily archived data. Due to the structure of the USGS datafiles, it was decided that two separate programs, one to create the input files for the current data, the other to create the input files for the archived data, would provide a simpler and more robust solution. As noted previously, each new USGS file already contains all of the information needed for the current data input file, because the USGS file contains data for the most recent approximately 24 hours. Thus, the program creating the current data input file only needs to deal with the most recent USGS file from a given USGS station. On the other hand, the program to create the archived daily data input file, while performing the similar operations of data extraction and XML conversion, needs to deal with multiple files from the same USGS station, and may also have to deal with more complicated situations, such as a restarting of the data transfer after a stoppage.

Because the programs would need to run in a UNIX environment, they were both written in the PERL language. Four directories (folders) were used. The USGS datafiles were transferred to a directory that, under normal circumstances, would contain only the most recent files. The current data program operated on these files shortly after the transfer ended, producing the two XML current data input files, one for the stage, and one for the discharge, which were placed in two different directories for XML files. At the end, the program moved all of these files to a fourth directory that acted as short term storage of the USGS files. This program runs every hour. If under abnormal conditions files other than the most recent are within the transfer directory, the current data program should still function properly; it simply searches for the most recent file corresponding to any given station.

The archived data program runs only once per day. As of this writing, it runs at 9:00 a.m., thus allowing stations that have unusually long lag times to be included. The program operates on the files stored in short-term storage directory, aggregates the daily data from multiple files at each station, and then writes out the XML archived daily files, one for the stage, and the other for the discharge to subdirectories in the two XML directories.

The XML input files produced by the two programs are identical to those produced by the original Visual Basic program except in one regard. An additional field has been added to each datapoint specifying the date corresponding to the datapoint. As noted in the previous section, this allows the display program to give the date of the most recent datapoint in the pop-up window and the larger graph.

If new gaging stations are to be added, then the programs will need modifications because they assume a given total number of stations. The modifications should however be relatively minor compared to the modifications needed for the display program.

2.6. Summary

A web-based information tool has been developed to provide the most recent available data from the USGS on streamflows in Indiana, combined with relevant information regarding scour-critical bridges. Its earliest versions were accessible over the Internet in 2006, but these suffered from numerous interruptions due to issues related to the unreliable transfer of USGS data. With a number of changes to the implementation, particularly with regards to the handling of the data transfer from USGS, the current version has been running continuously since March 2009, with only a single brief interruption.

3. The truck-mounted scour-monitoring system

3.1. Background

3.1.1. The NCHRP truck

With scour monitoring being considered formally by the FHWA as a scour countermeasure, an NCHRP project 21-07 (Schall and Price, 2004) was initiated to examine various portable scour-monitoring technologies. Much of that study was devoted to the development of a truck-mounted scour-monitoring system. As described by Schall and Price (2004), it consisted of a Palfinger articulated-arm crane (model PK4501C) installed on a 2001 Ford F-450 truck (Fig. 3.1). For the current project, the entire truck-crane system was taken over from the NCHRP project.

Fig. 3.1: a) Schematic diagram of truck with articulating-arm crane over bridge, including reach dimensions, b) photograph of truck with crane in operation, c) close-up photograph of crane with 80-in stainless-steel pipe extension in which scour-monitoring sonar transducer is mounted (all figures taken from Schall and Price, 2004)

Fig. 3.1a indicates that the crane, when the truck is positioned a maximum of 3 ft from the side of the bridge, has a reach of approx. 21-ft below the bridge deck. The actual maximum operating distance for this configuration is somewhat larger because of an 18-in long rotator and a 80-in long stainless steel pipe (Fig. 3.1c) within which the scour sonar is mounted are attached to the end of the

crane arm. As a result, the maximum reach from the bridge deck to the water surface would be, under optimal conditions, closer to 29-ft with the scour sonar submerged.

If the truck is to be used when stationary, outriggers (see Fig. 3.1a) are deployed for stability. For a mobile application, e.g., when traversing the length of the bridge, the outriggers cannot be used. Instead, high-load castors (Fig. 3.2) were designed, fabricated, and installed, for mobile use. When not in use, these could be lifted out of the way, but could be deployed quickly when needed.

Fig. 3.2 One of pair of high-load stabilizing castors (taken from Schall and Price, 2005)

In addition to the truck-crane system described above, the basic sonar-monitoring system or mobile wireless streambed profiler, developed by ETi Instrument Systems Inc. for the NCHRP project, was also taken over for the current project. The system consisted of three basic components, i) a wireless sonar sounding assembly, ii) an ultrasonic acoustic stage sensor, and iii) a truck position sensor, together with the required electronics for data transmission. These are described more fully in the manufacturer-provided Technical Manual (ETi Instrument Inc., 2005), and the following will only give a brief overview of the most important aspects. Most of this chapter will focus on the new element developed for this project, namely the acoustic positioning system to determine the position of the crane when it is deployed.

Fig. 3.3 a) Sonar transducer, used in scour monitor, b) sideview of streamline body surrounding the stainless steel pipe transducer housing, c) bottom view of transducer housing (taken from Schall and Price, 2005)

3.1.2. The wireless sonar sounding assembly

The heart of the scour-monitoring system is the wireless sonar transducer (Fig. 3.3a). This is mounted at the bottom of stainless steel pipe (Fig. 3.3c), and when submerged in a stream emits and receives acoustic pulses that are used to determine the distance between the transducer and the streambed. In this way, the streambed can be profiled by traversing the profiler across the stream, and any scour holes in the path of the traverse can be identified. A freely swiveling streamlined-body shape

(Figs. 3.3b and 3.3c) surrounds the transducer housing, and is intended to minimize the drag on the submerged-pipe-transducer-housing and the consequent flow disturbance. According to specifications, the transducer operates at a frequency of 200 kHz with a beam width of 8° (@-3dB) at a rated RMS power of 600W. This beam width implies a probed area of diameter ≈ 1.4 -ft for a depth of 10 ft with the transducer aligned perfectly vertically, proportionally larger or smaller diameter for larger or smaller depths. Further, according to the manufacturer (ETI), the transducer should be used for distances greater than 2-ft.

3.1.3. The ultrasonic stage sensor

An ultrasonic stage sensor with a range of 2 ft to 50 ft is available for continuously determining the distance to the water surface. In the current configuration, this is mounted on a retractable beam (with the HEXAMITE acoustic receiver array, which will be described later) that, when deployed, projects over the edge of the bridge (see Figs. 3.6b and 4.6b). This information can be used for various purposes, including as a rough estimate of the vertical position of the scour sonar.

3.1.4. The truck position sensor

In order to maintain a historical record of the streambed profiles and scour, a positioning system to determine the position of the sonar monitor at any time is necessary. In the current project, the position is divided into two components, i) a local position, i.e., relative to the truck, and ii) the position of the truck along the bridge. The first will be discussed in greater detail below; the second, the truck position sensor, is part of the original NCHRP truck system. The truck position sensor uses a modified measurement wheel (Fig. 3.4), mounted on the rear of the wheel. A rotary encoder transforms the wheel rotation into a linear distance, with a resolution of 2.25 in, and the distance is transmitted with each scour sonar reading.

Fig. 3.4 Measurement wheel deployed at rear of truck (taken from Schall and Price, 2005)

3.1.5. The ETI electronics and data acquisition

The three components, the scour sonar, the stage sensor, and the truck-position sensor, are ultimately linked together through a master control unit (Fig. 3.5) which outputs a combined data string composed of data from all three components to a data acquisition computer via an RS232 port. Power to the scour sonar is drawn through a cable from a battery in an electronics enclosure that is mounted on the crane (Figs. 3.8 and 4.6). Data from the sonar are sent through the same cable to a wireless modem in the same enclosure (Fig. 3.8). The modem transmits the sonar data wirelessly to the master control unit, which is located in another enclosure attached to the truck-bed workstation. The stage sensor and the truck-position sensor are connected by separate cables to the master control unit.

The data string received through the RS232 port consists of four comma-separated ASCII values in the order i) sonar measurement in feet, rounded to the nearest tenth, ii) number of pulses from the truck-position sensor, iii) stage measurement in feet, rounded to the nearest tenth, and iv) the voltage of the battery to which the sonar is directly connected, rounded to the nearest tenth and then multiplied by 10. If a component is not connected, or is not operating properly, it will not send the appropriate data to the master control unit. In such a case, either a "timeout" message is sent to the

computer, or a nonsensical value, typically a very large number, will be reported. Although the ETI Technical Manual states that a data record is sent at a rate of one record per second, a rate of one good record every two second is currently more typical.

Fig. 3.5 Truck-bed workstation, to which ETI master control unit enclosure is attached

3.2. The acoustic (HEXAMITE) positioning system

3.2.1. Background

As noted above, the position of the scour sonar is needed for a reproducible scour record. As stated in the original NCHRP project report, "...a critical part of the articulated crane research was to develop a methodology to track the location of the end of the crane on a real-time mode as the crane was being operated." In the NCHRP project, it was specified that the desired positioning system should be able to determine the position of the end of the crane within 1-ft. In the NCHRP study, two low-cost (less than \$10,000) GPS systems were tested for tracking the end of the crane: a Trimble Pathfinder Pro XRS™ and a LEICA GS50. Both were found inadequate; differences in the horizontal during different tests were as high as 10 ft, while differences in the vertical could exceed 3 ft. The solution adopted in the NCHRP project was a combination of displacement sensors (linear draw wires and potentiometers with various gearing mechanisms) and tilt meters mounted on the crane that together would give the information necessary to determine the location of the end of the crane. In their conclusion, the NCHRP project authors remarked that "...this approach did create a system of multiple components that required a certain electronic aptitude to operate and maintain." They therefore suggested that "A simpler positioning system involving fewer components, ..., might be preferable if the required accuracy

was possible.” The present project was therefore motivated to develop a simpler system with fewer mechanical components with comparable accuracy. Discussions with ETI, the developer of the scour sonar system and contributor to the NCHRP project, led to the suggestion of an acoustic positioning system.

3.2.2. Conceptual basis of an acoustic positioning system

The conceptual basis of an acoustic positioning system lies in the acoustic distance measurement that is also at the heart of the scour sonar or stage sensor system. An acoustic signal is emitted from a transmitter, the position of which is to be determined, and received by receiver, the position of which is known. The distance between transmitter and receiver can therefore be estimated. If at least three receivers are placed at three independent positions, then the so measured distances to each of the receivers provide sufficient information as to allow the determination of the three spatial coordinates defining the position of the transmitter. The relevant equations are given in detail in Appendix C.

3.2.3. Implementation of an acoustic positioning system

Applied to the specific problem of tracking the end of crane, several complications arise. Because the scour sonar is submerged, and the housing is surrounded by a streamlined body, a transmitter cannot be placed exactly at the end of the crane, coincident with the scour sonar; it had to be attached on the stainless steel pipe some distance away from the scour sonar. Further, it could not be assumed in general that the stainless steel pipe would always be oriented vertically; it could be tilted at some angle to the vertical. In the NCHRP project, tiltmeters were used to measure the tilt. In the current acoustic system, a single transmitter would not allow determining the tilt with respect to the vertical of the sonar scour. It was therefore decided to implement the system with two acoustic transmitters that would be attached a fixed distance apart to the stainless steel pipe.

A minimum of three receivers is necessary for determining the position of each transmitter. In the current system, four receivers (Fig. 3.6) are used, the fourth receiver acting as a ‘redundant’ check. Thus, in actual operation, four different estimates of the position of any one transmitter are made. If any one estimate is substantially different from the others, then typically all estimates are discarded as unreliable. If all four estimates are sufficiently close to each other, then the four estimates are averaged, and the average is taken to be the best estimate of the position.

The center frequency of a transmitter/receiver is 40 kHz, with a total beam angle of 30° (-6dB). Because of the finite beam angle, some aiming of the transmitters/receivers will be necessary in order to obtain good signals. All four of the receivers should be within the beam angle of the transmitter, while both transmitters should be within the beam angle of each receiver. For greatest accuracy, the receivers should be as far apart as possible, but the beam angle requirement as well as practical mounting issues limited the span of the receiver array. In the current design, the receiver array was arranged in an approximately rectangular configuration that is 32.4-in × 46.5-in. The mount for each receiver in the array was designed such as to allow aiming without changing the position of the receiver. The entire array is intended to be mounted vertically. A point on the mount at approximately the center of the array is taken as the local origin (see Fig. 3.6) when determining spatial coordinates, i.e., all transmitter locations are determined relative to this point. If a different coordinate system is desired, e.g., such as one based on bridge coordinates, then it can be related to this local coordinate system. The array is deployed from a retractable beam on the truck (note that the ETI stage sensor is also deployed from this beam).

Power to the receiver array (as well as to the master control unit of the ETI system components) is drawn from a large main battery at the rear of the truck. Communication is provided through a

central cable running from a central connection box on the receiver array mount to the workstation, where it is tied to the cable from the transmitters, before going into the data acquisition computer through the RS232 port.

Fig. 3.6 a) elements of receiver array, b) receiver array mounted on a retractable beam on the truck (note that the ETI stage sensor is mounted on the other side of the beam)

Fig. 3.7. a) the two acoustic transmitters mounted in a pipe, b) transmitters + pipe attached to the to the stainless steel pipe extension housing the scour sonar

The two transmitters are mounted 37.25-in apart in a pipe that is attached to the larger stainless steel pipe housing the scour sonar (Fig. 3.7). The lower transmitter is 33.5-in from the sonar. The axes of the transmitter surfaces are not located on the axis of the sonar scour, but offset a small distance ($\approx$ 5-in). Communication and power to the transmitters are provided by means of a cable to the same enclosure housing the wireless modem for the scour sonar (Fig. 3.8). In this enclosure, the two corresponding HEXAMITE control units are also installed. Although the HEXAMITE system was supposed to have been able to synchronize themselves acoustically, and hence without cables, reliable operation was never achieved in this mode, and hence cables were necessary from the HEXAMITE units to the computer.

Fig. 3.8 Electronics enclosure to be mounted on crane arm, a) exterior showing connections, b) interior showing ETI modem, Hexamite units for transmitters, and 12 V battery

Each receiver or transmitter (six in all) is attached to a HEXAMITE control unit (Model HX900), which ensures an orderly operation of signal transmission, signal reception, timing, and data communication with the computer through an RS232 port. Details of the transmitted data and the configuration of the HEXAMITE units can be found in the HEXAMITE manuals available on the Internet; only the most relevant details are mentioned here. Software provided by the manufacturer is available to configure the units – if this software cannot configure the units, then this indicates a hardware problem. The use of the data acquisition software developed in this project assumes that the HEXAMITE units have been previously configured using the manufacturer's software. Whenever an acoustic transducer or a HEXAMITE unit is replaced, then the system needs to be reconfigured. Unlike the ETI datastream, the HEXAMITE datastream requires an initiation signal to be sent, after which a string of eight space-separated numbers in hexadecimal format is received, and appropriately converted. These are the times in terms of number of pulses taken for an acoustic pulse to travel from each transmitter to each of four receivers, which can be directly related to the distances between each transmitter-receiver pair. The pulses are driven at a frequency of 500 kHz, such that 10,000 pulses would correspond to 0.02-s

(which might correspond to a distance of ≈ 22 -ft). The spatial coordinates of the transmitters can then be determined from these distances if the coordinates of the receivers are known. Details are given in Appendix C.

3.3. Summary

An acoustic positioning system has been developed for the NCHRP truck-mounted scour-monitoring system in order to provide a system that would be easier for INDOT operators to use routinely. It is based on attaching two separate acoustic transmitters to the stainless-steel extension housing the scour sonar. These would emit acoustic signals that would be received by an array of four receivers, mounted at a fixed known location on the truck. Based on acoustic measurements of the distances between transmitters and receivers, the spatial coordinates of the transmitters could be determined, and hence the position of the sonar scour and the point on the streambed being probed.

4. Testing of the positioning system

Testing of the acoustic positioning system was performed both in the laboratory and to a more limited extent in the field. In the laboratory, only the positioning system, i.e., completely separated from the truck, was tested under relatively ideal static conditions. A reference or 'ground-truthing' was provided by Total station measurements. In the field, the positioning system was tested in combination with the other components (namely the ETI components), on the truck. Unfortunately, no independent reference was available, though consistency with the ETI component measurements and estimated stream gage height could be checked.

4.1. Laboratory testing

Before field testing of the HEXAMITE positioning system, laboratory testing was undertaken since this permitted more flexible and controlled testing. A preliminary test examined the level of fluctuations in the number of pulses, N_p , during a distance measurement by a given transmitter-receiver pair. It was found that, for $N_p > 6000$, the standard deviation when 100 readings were taken was generally less than 10 or 0.2%. Thus, provided an appropriate calibration could be determined for each transmitter-receiver pair, and near ideal conditions could be achieved, distances could be measured with quite high accuracy. It was noted however that, for one or two transmitter-receiver pair, a zero number of pulses was sporadically reported.

Fig. 4.1: Elements of the laboratory testing configuration, a) Receiver array mounted on upper floor with Total station and transmitters on lower floor, b) transmitters on a tripod

The major test investigated the ability of the HEXAMITE system to locate the two transmitters in space, in a comparison with locations determined using a surveying Total Station. The receiver array was mounted on an upper floor (Fig. 4.1a) and the pair of tripod-mounted transmitters (Fig. 4.1b) was placed at 16 different locations on the laboratory floor. A surveying Total Station system (Fig. 4.1a) was then used to determine the fixed spatial coordinates of each receiver and the variable spatial coordinates of each transmitter as the pair of transmitters were moved to different locations. At each transmitter location, 100 readings were taken, and the spatial coordinates as determined from the HEXAMITE system could be compared with the Total Station coordinates, which were taken as a reference or 'ground-truth'. In this test, the center of the receiver array was approximately 15-ft above the low transmitter, which was placed ≈ 2 -ft above the floor. The receiver array and the pair of transmitters were aimed at each other at the initial position (at $(x,y) \approx (6.5 \text{ ft}, 0 \text{ ft})$, where x is the coordinate direction perpendicular to the plane of the receiver array, and y is the horizontal coordinate perpendicular to the x -coordinate). When the pair of transmitters was subsequently moved to another location, no special effort was made to re-aim the transmitters, and their orientation was consequently similar to that in the initial position.

Fig. 4.2 Comparison of reference horizontal locations (determined from Total station measurements) and horizontal locations determined from HEXAMITE system, a) for the top transmitter, and b) for the bottom transmitter, at various locations. Numbers in parentheses indicate the percentage of readings at a given location that is within a distance of 0.5-ft (first number), and within a distance of 1-ft (second number) from the reference location.

The horizontal locations, averaged over the 100 readings at each location, of the transmitter pair as determined from the HEXAMITE system are compared with the Total Station results in Fig. 4.2. The axis of the center of the receiver array lies between $y = 0$ -ft and $y = 1$ ft. The measured locations were therefore taken on a line near this axis where $2\text{-ft} < x < 11\text{-ft}$ and also on a line perpendicular to this axis, at $x \approx 5\text{-ft}$, $-2\text{-ft} < y < 4\text{-ft}$. In Fig. 4.2, linked pairs of locations are shown. Where only a single location is shown without a corresponding linked location, the location determined from the HEXAMITE is very substantially wrong and out of range. For example, in Fig. 4.2a, this occurs at two locations, at $(x,y) = (2.4, 0.18)$ -ft, and at $(x,y) = (4.97, -1.9)$ -ft. At two other locations in Fig. 4.2a, at $(x,y) = (10.03, -0.07)$ -ft and at $(x,y) = (4.89, 3.46)$ -ft, the distance between the HEXAMITE-determined location and the reference location is larger than 1-ft. Nevertheless, along the axis, in the region, $3.5\text{-ft} < x < 9\text{-ft}$, and perpendicular to the axis, in the region, $-1.5\text{-ft} < y < 2.5\text{-ft}$, differences between averaged HEXAMITE and Total Station determined locations for both top and bottom transmitters were less than the 1-ft

criterion specified in the NCHRP project. The slightly larger extent of the working region in the x -direction is consistent with the slightly larger separation of the receivers in the vertical.

The difference in the vertical locations, $(z_{\text{HEX}} - z_{\text{Tot}})$, determined by the HEXAMITE system and by the Total Station for the 16 measurement locations is plotted in Fig. 4.3 for both top and bottom transmitters. Again, where measurements are missing (as for Measurement numbers 5, 6, and 13) indicates that the HEXAMITE determined z -coordinate is very largely wrong. Because $z < 0$, $(z_{\text{HEX}} - z_{\text{Tot}}) > 0$ implies that the HEXAMITE system tends to measure a higher elevation than that measured by the Total Station. At all locations where the averaged HEXAMITE-determined horizontal locations were within 1-ft of the Total-station-determined horizontal locations, the averaged HEXAMITE-determined vertical location was within 1-ft of the Total-Station-determined vertical location.

Fig. 4.3 Difference in elevations determined from Hexamite system and determined from the Total station ($\times$ top transmitter, Δ bottom transmitter); note that $(z_{\text{HEX}} - z_{\text{Tot}}) > 0$ means that the elevation from the HEXAMITE system is higher than the elevation from the Total Station.

The comparisons so far discussed have been between HEXAMITE-system results averaged over the 100 readings at each location. In the field, the more usual situation would involve a single reading at each location, and so it would be of interest to examine the extent to which individual single HEXAMITE reading differ from the Total Station reference measurements. In Fig. 4.2, each linked-pair of location is associated with a pair of values in parentheses. These indicate the percentage of the total number (100) of HEXAMITE readings within 0.5-ft (the first value) and within 1-ft (the second value) of the Total-Station reference. For example, in Fig. 4.2a, for the location at $(x, y) = (4.8, 1.7)$, 76 of the 100 readings were within a distance of 0.5-ft, while 100 of the 100 readings were within a distance of 1-ft. Thus, even with the more stringent condition that not only average but also individual readings should be within 1-ft of the reference value, there remains a substantial working region, conservatively estimated to be a 3-ft diameter region, that would satisfy this requirement for a large fraction of individual readings. At all of the measurement locations excepting 4, 5, 12 and 13 (corresponding to $(x, y) = (2.42, 0.18)$, $(10.04, -0.07)$, $(4.94, 2.52)$, $(4.97, -1.9)$, namely at the extremes of the working region), all 100 of the HEXAMITE z -readings were within 1-ft of the reference values.

As can be seen in Fig.4.2, the HEXAMITE system tends to overestimate the values of x , and outside of the near-axis region, also tends to overestimate the values of y . At the same time, it

consistently underestimates the z -values. This may to a certain extent be an issue of the definition of coordinate axes. Thus, while distances might be correctly measured by the acoustic system, the partition into the different coordinate directions may be problematic. Some of this might be due to an inexact conversion of the coordinate system as defined by the Total Station to the coordinate system defined with respect to the receiver array. It should also be mentioned that while the Total Station results have been taken as reference values, some uncertainties are associated with them because the reflectors used to determine the locations could not be placed at the exact locations of the transmitters/receivers, and these offsets were neglected in the reported values. These are however all expected to be less than 0.25-ft and hence could not explain all of the discrepancies observed. There was also no pre-screening of the HEXAMITE data that would automatically discard readings that were obviously wrong; such pre-screening might have been expected to improve the performance statistics in the borderline region.

While the accuracy of the HEXAMITE positioning system in determining the locations of the transmitters/receivers seems adequate from the results of the above tests, it is ultimately the location of the point on the stream bed probed by the sonar that is of primary interest, and not just the locations of the transmitters/receivers. It is expected that the determination of the probed point might be much less accurate than the determination of the locations of the transmitters/receivers because errors in the determination of the latter will be amplified. The errors incurred in determining the location of the probed point depends on the distance, L_b , to the streambed measured by the sonar scour, with larger L_b leading to larger errors. Not only can the individual errors in the locations of top and bottom transmitters combine, but the combined error is further extrapolated to the streambed. To examine such errors, a value of $L_b = 10$ -ft was assumed, and for each measurement location, the predicted horizontal locations based on the Total-Station results and based on the HEXAMITE system were determined.

Fig. 4.4 Comparison of a) reference horizontal location of probed point on streambed with horizontal location determined from HEXAMITE system measurements (numbers in parentheses indicate the percentage of readings at any given location that is within a horizontal distance of 1.5-ft and within 1-ft in elevation (first number), and within a horizontal distance of 2-ft and within 1.5-ft in elevation (second number), from the Total station derived estimate, b) difference in elevation determined from the HEXAMITE system and from the Total station measurements. Note that a sonar scour measurement of 10-ft was assumed in calculating these coordinates.

The results for the horizontal locations are shown in Fig. 4.4; for clarity, the measurements at locations already known to be problematic, those at the edges of the measured regions have been omitted in Fig. 4.4. A deterioration of the predictions is evident, with larger distances between the HEXAMITE-predicted and the Total-Station-predicted locations. Only averaged measurements at two of

the 16 original locations would satisfy the criterion of being within 1-ft of the true ('Total-station') locations, though these two points, at $(x,y) = (7.3, 0.1)$ and $(4.8, 2.8)$, are rather curiously quite separated. If the criterion is relaxed to being within 1.5-ft, then on average, a notably more expanded working region is found, with eight of the stations satisfying the relaxed criterion on horizontal location. The results on the HEXAMITE predictions of the z - or bed elevation values are shown in Fig. 4.4b as differences from the reference values. Elevations continue to be underestimated, i.e., $(z_{HEX} - z_{Tot}) > 0$, but 9 locations are on average within 1-ft and 12 within 1.5 ft.

What is desired is a correct prediction of the three spatial coordinates, (x,y,z) , rather than the horizontal and the elevation coordinates independently, and these with a single measurement rather than over an average over multiple measurements. At each paired coordinates in Fig. 4.4 is indicated in parenthesis two values, the first is the percentage of readings within 1.5-ft in the horizontal, and at the same time within 1-ft in the vertical, of the reference value, while the second is the percentage of readings with 2-ft in the horizontal, and at the same time within 1.5 ft in the vertical. If the looser criterion, being within 2-ft in the horizontal and within 1.5 ft in the vertical, is taken, then there remains a sizeable working region; a more stringent criterion would lead to a much more restricted region.

4.2. Field testing of the HEXAMITE positioning system

The laboratory tests examined only the (potential) performance of the HEXAMITE system under rather idealized conditions. Field testing, here broadly defined in terms of studies with the HEXAMITE system mounted on the truck, was also necessary, but in some respects was more limited due to practical difficulties (discussed below). Two types of field studies were undertaken. Much work was done with the HEXAMITE receiver array mounted on the truck and the transmitters mounted on the crane, but with the truck in a parking lot (of the Bowen Laboratory at Purdue University). The default approach to calibrating the HEXAMITE system (see Appendix C) was developed, and a large part of the data acquisition software was tested and debugged in this way. Some 'debugging' of the entire truck system was also done, motivating a number of small changes, e.g., improved waterproofing of the electronics associated with the measuring wheel, as well as of the ETI master control unit. Much more limited was testing of the entire system including software at bridge sites. These were done at two sites, SR225 over Burnett Creek, and SR18 over the Tippecanoe River, both chosen because of the close proximity to Purdue University, their relatively low traffic and wide shoulders. The SR225 site generally had insufficient water flow to submerge the scour sonar for testing, but did allow some testing of HEXAMITE system in a more convenient smaller-scale setting. The main testing of the entire system was however carried out at the SR18 site during the winter of 2008-2009, when there was sufficient flow for the sonar scour to be submerged, hence allowing the entire bed profiling system to be tested. The following is therefore mainly restricted to work at the SR18 site.

During the initial attempt at the SR 18 site, difficulties were experienced in obtaining any usable signal from the HEXAMITE system and so no data was collected. This was attributed to inexperience in aiming the transmitters and receivers. In the laboratory (or in the parking lot), easy access to the receivers and particularly to the transmitters meant that aiming was a relatively straightforward process. On a bridge deck over a flowing stream, with the crane and the transmitters over the side of the bridge, access to the transmitters was not possible. Pre-aiming with the crane still on the bridge deck was also not feasible because of the substantial change in receiver-transmitter geometry with the crane deployed over the bridge side. Inexperience at precisely and smoothly controlling the crane and rotator added to the difficulties.

Two solutions were considered to aid in aiming. The first was based on a knowledge prior to deployment of the approximate receiver-transmitter geometry when the transmitters were deployed.

This required an estimate of the distance to the water surface, which was available from the stage sensor, as well as the horizontal distance of the transmitters from the receiver array, which can be maintained constant and so could be determined from the bridge deck. The angle of the transmitters (and receivers) with respect to the horizontal could therefore be set while the transmitters were still on the bridge deck. The second aid in aiming that was tried was a mini-video camera that was mounted atop one of the transmitters (Fig. 4.5). Thus, if the receiver array was centered in the field of view of the camera when the transmitters were deployed, then the transmitters would be considered properly aimed.

From a subsequent test site visit, it was found that the first solution was entirely adequate, and surprisingly good-quality signals were obtained without substantial effort in aiming, i.e., manipulating the crane-rotator to an appropriate orientation, once the appropriate angle with respect to the horizontal of the transmitters and receivers were set prior to deployment. For this reason, in the data acquisition software to be used with the system, a recommended angle is estimated from the ETI stage sensor reading. The camera solution was still studied, but with inconclusive results. The camera used was available from a past project, and hence was not chosen specifically as an aid to aiming. Hence, the fixed focus lens was too wide, and the quality of the images was of insufficiently high quality that it offered little help to the operator of the crane in aiming. The camera solution might nevertheless be considered in the future as a possible enhancement of the system.

Fig. 4.5 Transmitters on stainless steel pipe extension, with mini-camera mounted on top of bottom transmitter

4.2.1. Results from field testing I: Stationary-truck tests

The following results were taken on 17 Feb. 2009 at the SR18 site. Fig. 4.6 shows the crane deployed and the scour sonar submerged in a stationary-truck situation. The site is also a USGS gaging site (No. 03333050), and a gage height of 4.35-ft was measured on 26 Feb. 2009, when the discharge was however substantially lower (approx. 1200 cfs lower), and so based on historical record of gage height vs discharge, the gage height on 17 Feb. 2009 was estimated to be 5.2-ft. The gage height is not necessarily identical to the (maximum) depth, but is generally slightly in excess of the maximum depth.

Two types of measurements were made with the truck-mounted system. In the first, the truck was stationary with the outriggers extended – this case is similar to that in the laboratory (or in the parking lot) in which the position of the transmitters should be constant, and because the truck was stationary, all results should also be approximately constant. Two sets of readings were taken, each done over a duration of ≈ 100 s, thus allowing a comparison between what might be considered replicates. In the second type of measurement, the truck slowly traversed the bridge, with the crane deployed but in an unchanging configuration – the crane with the scour sonar was towed in the stream in nominally the same position relative to the receiver array. In this case, the local coordinates of the transmitters, i.e., relative to the array, should remain the same, though the scour sonar reading should change depending on the streambed elevation.

Summary statistics of the horizontal coordinates of the top and bottom transmitters as well as the probed point on the streambed, obtained in two sets of stationary-truck measurements, are shown

in Tables 4.1 and 4.2. During the stationary-truck tests, the ETI stage sensor reading was constant at 23.3 ft. For Test 1, the sample size was 165, while for Test 2, it was 108, each sample taken for the same 100 s duration. The sonar scour reading was constant at 2.5-ft. It should be noted that the field measurements differed from the laboratory measurements in two significant aspects. First, while in the laboratory, a separate calibration coefficient was used for each individual transmitter-receiver pair, in the field, the default calibration method (see Appendix C) was chosen. In this method, pre-calibrated offsets were used together with a common temperature calibration (no special site-specific calibration was performed in the field). Secondly, a pre-screening of the data was performed, in which evidently unreliable data were immediately discarded. The criteria for discarding data are listed in Appendix C. Also unlike the laboratory measurements, no systematic ‘ground-truth’ measurements was performed, and so a reference ‘true’ value is not available. In the following analysis, it was assumed that the average value in each set of data was a good estimate of the ‘true’ value, and this was used as a reference value. A comparison of the statistics of the two tests (Tables 4.1 and 4.2) shows that the average values (in fact all of the summary statistics) of the coordinates are quite close, indicating firstly that the measurements are reproducible, and also supporting that the average values are good candidates for reference values.

Fig. 4.6: The truck with the HEXAMITE positioning system, a) the transmitters and the crane-mounted electronics enclosure, b) the receiver array (and ETI stage sensor) projecting over the side of the bridge

The pre-screened data for the horizontal coordinates are plotted in Fig. 4.7. For the top transmitter in Test 1, the scatter is relatively compact. The scatter increases for the bottom transmitter, and becomes quite substantial when the transmitter measurements are combined with the scour sonar measurement to infer the horizontal coordinates of the probed point. For Test 2, the same general

trend of the scatter is noted, but the level of scatter seemed to have increased for all points. In the upper right corner of each subfigure for the transmitter locations is the percentage of points within 1-ft of the horizontal reference value and within 1-ft of the elevation reference value (i.e., the average values). For the transmitters, a relatively large percentage, all above 90% except for the bottom transmitter in Test 2, satisfies this criterion that was specified in the previous NCHRP project. For the probed point, a looser criterion of being within 2-ft of horizontal reference and within 1.5 ft of the elevation reference was applied, but even with this looser criterion, only 82% of the data in Test 2 was satisfactory.

Table 4.1: Statistics of the local horizontal coordinates of the top and bottom transmitters and the probe point on the streambed, as determined or inferred from the HEXAMITE system in Test 1

	top transmitter			bottom transmitter			probed point on streambed		
	x (ft)	y (ft)	z (ft)	x (ft)	y (ft)	z (ft)	x (ft)	y (ft)	z (ft)
average	9.22	2.42	-20.52	10.27	2.54	-23.11	11.96	2.76	-27.75
standard deviation	0.27	0.18	0.13	0.41	0.26	0.18	1.01	0.78	0.44
maximum	10.16	2.84	-20.12	11.34	3.41	-22.52	13.46	5.38	-26.80
minimum	8.69	1.88	-20.84	8.08	1.38	-23.80	6.99	-0.04	-29.31

Table 4.2: Statistics of the local horizontal coordinates of the top and bottom transmitters and the probe point on the streambed, as determined or inferred from the HEXAMITE system in Test 2

	top transmitter			bottom transmitter			probed point on streambed		
	x (ft)	y (ft)	z (ft)	x (ft)	y (ft)	z (ft)	x (ft)	y (ft)	z (ft)
average	9.35	2.54	-20.49	10.09	2.70	-23.8	11.41	2.98	-28.01
standard deviation	0.46	0.32	0.21	0.59	0.39	0.26	1.35	1.02	0.60
maximum	10.90	3.55	-19.74	11.17	3.57	-22.65	13.66	5.15	-26.67
minimum	7.8	1.56	-21.12	8.24	1.07	-23.99	6.41	-0.80	-30.19

The estimated elevations of the two transmitters and the probed point on the bed are plotted in Fig. 4.8 against the local x -coordinate. There is a strong correlation between the estimated x -coordinate and the estimated z -coordinate. This may be attributed to the HEXAMITE sytem being based on distance measurements. Thus, for the same distance, a larger x -value will be associated with a smaller z -value as seen in Fig. 4.8. It is also clear that the scatter in the x - and z -values of the bed will be amplified from the scatter in the transmitters.

The statistics in Tables 4.1 and 4.2 as well as Fig. 4.7 suggest that the pipe housing the scour sonar and to which the transmitters are clamped is slightly tilted away from the receiver array, $\approx 20^\circ$ to the vertical, though the scatter is such that it may not be justified to conclude that the differences in horizontal coordinates of the top and bottom transmitters are statistically significant. Such small tilts are nevertheless difficult to verify visually, but may have a significant influence on both the horizontal

and vertical coordinates of the probed point, and were the motivation for the use of tilt meters in the previous NCHRP project.

Fig. 4.7 Horizontal coordinates, measured or inferred using the HEXAMITE system, a) top transmitter, b) bottom transmitter, and c) the probed point on the streambed.

Fig. 4.8 Variation of elevations, z , of transmitters (top and bottom) and the probed point on the bed with perpendicular distance from receiver array (x) in a) Test 1, and b) Test 2.

While no ‘ground-truth’ measurements were made in the field, a rough consistency check may be made using the ETI stage sensor and scour sonar measurements. The ETI stage sensor reported a constant distance of 23.3 ft to the water surface. There is a slight offset of 0.3 ft between the elevations of the face of the sensor and the local origin of the receiver array, and so, in terms of the local coordinates, the water surface is located at $z=-23.7$ ft, i.e., 23.7-ft below the local origin. Guided by the photograph in Fig. 4.6, the swiveling streamlined body attached to the end of the stainless steel pipe is mostly but not entirely submerged. This suggests that the elevation of the lower transmitter should be higher than the averaged values given in Tables 4.1 and 4.2, possibly even up to 1 ft, since the lower transmitter should be well above the water surface. The source of this discrepancy is not clear, but this is further discussed after the presentation of the moving-truck results. If it is further assumed that the scour sonar is ≈ 1 -ft submerged, estimated from the degree of submergence of the streamlined body, and also that the sonar is vertical, then according to the ETI stage sensor + scour sonar, the bed elevation should be (in local coordinates) -27.2-ft, to be compared with the averaged bed elevations of -27.7-ft from Test 1 and -28.0-ft from Test 2.

4.2.2. Results from field testing II: Moving-truck tests

The second type of measurement made involves a moving truck trawling the crane/scour sonar in a nominally fixed position relative to the receiver array. One possibly important difference between the stationary-truck and the moving-truck cases is that, when the truck is moving, the stabilizing outriggers are retracted and are replaced by high-load castors. Only one traverse was performed. Because the crane position was unchanged during the operation, the local position of the transmitters should remain roughly the same. The position of the truck along the bridge is determined from the wheel sensor. The truck started in the general vicinity where the preceding stationary-truck tests were conducted, and then moved in the westbound direction, i.e., the same as the traffic. The ETI stage sensor reading varied from 23.3-ft at the beginning of the traverse to 23.2-ft towards the middle and finished at 23.4-ft at the end, as might be expected, very similar to that measured during the stationary-truck tests. The small variation may however indicate some differences in elevation of the bridge deck along the bridge. The scour sonar reading started at 2.8 ft at the beginning of the traverse, reached a maximum of 4 ft, and then decreased again to 3.5 ft at the end. In the moving-truck case, the truck started the traverse in the vicinity where the stationary-truck tests were performed. The larger scour sonar reading suggests that, in the moving-truck test, the sonar was likely less submerged than in the stationary-truck test. It should be noted that the entire stream was not traversed, since both the start and end end of the traverse was located some distance from the banks in order to avoid very shallow regions; the total length of the traverse was ≈ 117 ft (corresponding to a total measurement duration of ≈ 100 s).

Table 4.3: Statistics of the local horizontal coordinates of the top and bottom transmitters as determined or inferred from the HEXAMITE system in the moving-truck test

	top transmitter			bottom transmitter		
	x (ft)	y (ft)	z (ft)	x (ft)	y (ft)	z (ft)
average	10.33	3.94	-19.33	11.27	4.27	-21.93
standard deviation	0.307	0.25	0.16	0.36	0.30	0.18
maximum	11.51	4.60	-18.60	12.12	4.93	-21.58
minimum	9.63	3.44	-19.68	10.05	3.44	-22.49

The summary statistics of the horizontal coordinates are shown in Table 4.3. The general characteristics are similar to those of the stationary-truck tests. The horizontal locations are somewhat farther from the receiver both in the x - and the y -directions. That the coordinates are different is not surprising since no effort was made to start at a location very close to the stationary-truck tests. Nevertheless, the elevation of the bottom transmitter can be compared with the elevation of water surface as measured by the ETI stage sensor (≈ -23.6 -ft including offset). In this respect, the results in Table 4.3 for the elevation of the bottom transmitter seem more reliable than were the results in the stationary-truck case.

Fig. 4.9 Measured horizontal coordinates in moving-truck case (crane not moved), a) top transmitter, b) bottom transmitter (numbers in upper right corner refer to the percentage of measurements within 1-ft of averaged horizontal location and 1-ft of averaged vertical location)

Fig. 4.10 Measured vertical coordinates plotted against measured local x -coordinate in moving-truck case for both transmitters

The pre-screened measurements (97 in total over the 100-s duration) for the top and the bottom transmitters are shown in Fig. 4.9. As in the stationary-truck results, the scatter in the top transmitter position is quite compact, and increases somewhat for the lower transmitter. The percentages of measurements within 1-ft in the horizontal direction and within 1-ft in the vertical direction of the averaged reference values, indicated in the upper right corner of the subfigures, are also quite high (equal to or above 95%). The behavior of the elevation coordinates (Fig. 4.10) is also quite similar to that previously seen in the stationary-truck case, notably the distinct correlation with the x -coordinate and similar scatter.

Fig. 4.11 Location of probed point on streambed determined using the HEXAMITE system, a) horizontal location, b) vertical coordinate vs distance along bridge (x_b), arbitrary origin

In the moving-truck test, the bed coordinates vary with distance along the bridge (x_b), and so these are treated separately. Fig. 4.11a shows the horizontal coordinates, while Fig. 4.11b shows the corresponding elevation coordinates, all with only pre-screening performed. The origin of the x_b -axis was arbitrarily set at whatever location the truck started, and so x_b is not the bridge profile coordinates. As seen previously with the stationary-truck data, the scatter is substantial, and as such is not necessarily most useful as an indication of the variation of the streambed. The corresponding post-processed (smoothed) data, after elimination of points considered to vary too quickly and then applying a five-point moving average filter, are shown in Fig. 4.12. The probed point seems to be oscillating to some extent in the streamwise direction as the sonar is being towed. It should be noted that the stainless-steel pipe extension is not rigidly mounted on to the crane rotator – some noticeable flex is observed as

it is being deployed. Hence some movement of the extension (and hence of the probed point) might be expected when the extension is being towed in the water (and possibly even when it is stationary).

Fig. 4.12 Post-processed (bad points removed and then moving-average filtered) coordinates of the probed point on the streambed, a) horizontal coordinates, b) vertical coordinate vs the distance along the bridge (arbitrary origin)

Also plotted in Fig. 4.12b. are estimates of the bed elevation based on the ETI stage sensor and the sonar scour readings, similar to that obtained in the stationary-truck case. In general, the bed elevations inferred from the HEXAMITE measurements are higher than were estimated by the ETI measurements. This contrasts with the behavior noted in the stationary-truck case, where the HEXAMITE system tended to predict bed elevations lower than an estimate based on ETI measurements. The differences are discussed below but are generally within 0.5 ft, and the two profiles exhibit similar trends. The statistics of the differences in the two estimates are summarized in Table 4.3. It should be emphasized that the ETI-based measurements should not be considered as 'ground-truth' as they are based on assumptions regarding the degree of submergence and the orientation of the scour sonar.

Table 4.3: Statistics of differences in the bed elevations determined from the HEXAMITE system and the ETI stage sensor + scour sonar

Average difference (ft)	standard deviation (ft)	maximum (ft)	minimum (ft)
0.41	0.18	0.77	-0.21

The difference between the different elevation estimates when the truck is stationary and when the truck is moving is believed to be at least partially related to the use of the outriggers when the truck

is stationary and the use of the high-load castors when the truck is moving, since this is thought to be the main difference in the two operations. Because the ETI stage sensor reading is found not to be substantially changed whether the truck is moving or stationary, a change in elevation of the receiver array and hence in the local origin would not explain the difference. With the outriggers extended however, a slight rotation of the truck bed does occur, which would lead to a rotation of the local coordinate system. For the same transmitter location, and hence almost identical measured distances between transmitter and receiver, a rotation of coordinate system would yield smaller values for the x -coordinate and lower elevations, which is what was observed in the stationary-truck tests. While this needs to be further investigated, it suggests that greater care and attention should be paid to the orientation of the receiver array frame, if this is to be used as a reference plane for the definition of the local coordinate system.

Finally a comparison with the estimated gage height may be made. The maximum depth estimated from the USGS gage heights is ≈ 5 ft while the maximum scour sonar reading was 4 ft, which would be the case if the scour sonar was submerged about 1-ft. As noted above, the scour sonar was likely submerged to a lesser depth than in the stationary-truck tests because the scour sonar readings near the region where those tests were done were larger than during the stationary-truck tests.

4.3. Further observations and concerns

The above tests were restricted to cases where the relative position of the crane with respect to the receiver array was fixed, and indicated that reasonable results, certainly for the locations of the transmitters, and probably for the location of the probed point on the streambed, could be so obtained. Very limited attempts were made to address the more difficult problem of locating the position of a continuously moving crane. This would be desirable for dealing with scour around a specific structure, such as a pier or an abutment. The attempts were generally not successful, because the range of crane motion within which the acoustic signal remained acceptable was quite limited if no re-aiming of the transmitters is performed. It may be that if a convenient and reliable means of re-aiming the transmitters could be devised, e.g., the use of a transmitter-mounted camera suggested earlier, then this would allow a type of crane motion in which the crane would be moved to a position, the transmitters re-aimed, measurements taken at a fixed position, and so on, rather than a continuous motion. Alternatively, a series of traverses may be made with the crane (and scour sonar) placed at different locations in the direction away from the bridge. This may however be constrained by the extension length of the crane.

An issue of some concern is the reliability of the hardware, particularly the HEXAMITE units. The first set of HEXAMITE units (and acoustic transmitters and receivers) worked well during the early years of the project, and only a limited number of spare units were acquired for contingencies. Unfortunately, a recent series of hardware failures occurred, particularly of the spare units, raising concerns about reliability. As a result, all spare units were exhausted, and because further funding for additional units was unavailable, this series of hardware failures also precluded any further testing, particularly field measurements, after those reported above. It also means that the system is currently not operational because at least one of the units is defective. While the acoustic transmitters and receivers are generic, and can be sourced from different manufacturers, the HEXAMITE units are proprietary, and no comparable units (at least at this price point) is available elsewhere.

4.4. Summary

Laboratory and field tests were undertaken to study of the performance of the developed acoustic positioning system. In the laboratory tests, the system was studied in isolation, separate from

the truck and the other system components, under rather ideal conditions. In comparison to reference coordinates determined independently using a Total station, the acoustic system was found capable of locating the position of transmitters within the limits of 1-ft in the horizontal and 1-ft in the vertical. If the uncertainty in the location of the probed point on the streambed is however considered, these criteria may not be satisfied to the same extent due to the amplification of the errors in extrapolating to the bottom.

Field measurements with the entire system were found to be substantially noisier. By appropriate pre-screening of the data, the noise can be reduced, such as to recover evidently degraded though more comparable performance in the field as in the laboratory at least with regards to the locations of the transmitters. Even with the pre-screened data, the inferred coordinates of the probed point on the streambed remain noisy, though some of the variation may reflect real variation due to possible fluctuations in the location of the scour sonar as a result of the action of the streamflow. Post-processing of the pre-screened data could be applied to produce a more easily interpretable streambed profile.

5. Summary and implementation plans

The project aimed i) to further develop the NCHRP truck-mounted scour-monitoring system with an alternate easier-to-operate system to track the location of the end of the crane, and ii) to develop a web-based program that would provide quasi-real-time information regarding streamflows in Indiana, combined with relevant bridge information, as a decision-support tool for effective deployment of the truck system.

5.1. The positioning system

An acoustic positioning system was developed and tested in the laboratory and in the field, together with the necessary data acquisition software. Under laboratory conditions, it was found that the system could track transmitters (acting as a surrogate for the end of the crane) within the limited specified in the previous NCHRP project, i.e., within 1-ft in the horizontal and 1-ft in the vertical. Because uncertainties and errors in locating the transmitters are amplified when the position of the point on the streambed being probed by the scour sonar is being determined, uncertainties in the location of the probed point may exceed the NCHRP specification.

Field testing indicated that the acoustic signals could be substantially noisier in the field. Prescreening of the transmitter-location data was applied to remove evidently unreliable data with the result that the locations of the transmitters could again be determined with reasonable accuracy, satisfying the NCHRP specifications. The position of the probed point on the streambed still exhibited an undesirable degree of scatter. To alleviate the remaining scatter, postprocessing of the position of the probed point was performed so as to remove points that were considered to vary too quickly (spikes), and thereafter to apply a moving-average smoothing filter. The postprocessing operations did not change significantly the average values which were assumed to be the best estimate of the true position of the probed point.

5.2. The web application

The web application, written in Macromedia (now Adobe) Flash 7 and supplemented by Perl programs, all running in a UNIX environment, combined the latest available USGS streamflow data with relevant bridge information, and has been continuously running since mid-March 2009 with only a single brief interruption of service.

5.3. Plans for implementation

5.3.1. Web application

With the web application already accessible over the Internet, and operating reliably for already a few months, it is considered already implemented. Further work on the web application might include any updating of the bridge database, and providing other relevant bridge information if desired. More extensive work might involve a better more automatic means of adding new bridge and stream gaging sites (currently this would require rather substantial intervention in the code rather than only in the input), and addition of other relevant layers of information, e.g., rainfall information.

5.3.2. Truck-mounted scour-monitoring system

Specific implementation plans for the truck-mounted scour-monitoring system, in general, and the acoustic positioning system in particular are still under consideration. At the last meeting of the Study Advisory Committee (February 2009), it was generally agreed that the system was still desirable,

but further testing would definitely be needed before the system could be adopted for routine operation. A more gradual transition might be considered in which the Research Division would be involved in any further testing and development.

6. References

ETI Instrument Systems Inc. (2005). Mobile Wireless Streambed Profiler Technical Manual, Fort Collins, CO.

Hexamite manuals at <http://www.hexamite.com/hx9.htm>.

Schall, J. D. and Price, G. R. (2004). *Portable Scour Monitoring Equipment*, NCHRP Rept. 515, Transportation Research Board, Washington, D. C.

Appendices

A. Assembling the system

The assembly of the truck-mounted scour-monitoring system is generally straightforward; the following lists the basic steps and gives suggestions that might facilitate the assembly.

A.1 The crane-mounted electronics enclosure box, the sonar, and the acoustic transmitters

1. From its parked position, the crane is maneuvered into a position to allow first the mounting of the crane-mounted electronics enclosure onto a cylindrical pipe (Fig. A.1a). The crane arm should be relatively vertical to facilitate this (Fig. A.1b).
2. The HEXAMITE output cable from the top of the enclosure box (from the cable reel) should then be connected to the cable on the crane arm (Fig. A.1c and d) that leads to the truck-bed workstation. This may require further maneuvering of the crane arm to facilitate this.

Fig. A.1 a) Crane arm with cylindrical pipe fixture, b) attaching the electronics enclosure box to the cylindrical pipe fixture, c) connecting the HEXAMITE output cable to a cable connector (leading to computer), d) detail of cable connection.

3. The stainless steel pipe extension housing the sonar scour may now be mated to the rotator. The rotator should be fairly low, 3-ft to 4-ft from the ground, and at a comfortable angle (Fig. A.2a). The pipe extension is fixed to the rotator with a bolt, so the bolt holes on both the extension and rotator should be carefully aligned.

- If the mating surfaces are corroded, some sanding of the surfaces is recommended.
- Lubricating the mating surfaces, e.g., with WD-40, may also be helpful.
- Once the mating has been partially performed, a guide pin may be hammered into the pin hole to complete the mating (Fig. A.2c), after which a nut can be introduced and the extension bolted onto the rotator (Fig. A.2d).

Fig. A.2 a) maneuvering the crane arm into position, b) attaching the extension to the rotator, c) hammering a guide pin prior to bolt placement, d) successful bolting together of extension and rotator, e) carefully tying and routing excess sonar cable, and f) connecting sonar cable to electronics enclosure box

4. The cables from the scour sonar may then be connected to the electronics enclosure (Fig. A.2f). The connections differ (the sonar cable has three prongs, while the transmitter cables have four prongs), and hence it should not be possible to misconnect the cables. Some care should however be exercised in tying and routing the cables to the crane (Fig. A.2e), so as to minimize the possibility of the cables being damaged or severed when the sonar is being deployed or retrieved.

Fig. A.3 a) Attaching the steel pipe with the two acoustic transmitters to the extension by means of clamps, b) connecting the transmitter cable to the electronics enclosure (after carefully tying and routing excess cable), c) completely connected system

5. The pipe with the acoustic transmitters may then be attached to the pipe extension (Fig. A.3a), and its cable connected to the other input port of the electronics enclosure box (Fig. A.3b).
6. The power to the scour sonar and acoustic transmitters may now be switched on (switch is on side of enclosure) before being deployed.

A.2 The measurement wheel

1. If the application requires the measurement wheel, then this, which is stored in one of truck boxes, can be connected at the rear of the truck (Fig. A.4b) with a pin. The wheel also has a data cable which needs to be mated to a connection on the truck.

A.3 The receiver array

1. The acoustic receiver array can be mounted independently of the acoustic transmitters. Depending on how the array has been stored, the procedure is slightly different. If the array has been stored with the receivers on the frame, then all that is necessary is to attach the frame with the receivers onto the retractable beam (Fig. A.4a).
 - a. If the receivers have been taken from the frame and stored in the truck boxes, then the receivers will need to be attached to the frame, and then the cable from each receiver need to be connected to the central connection point (Fig. 3.6a).

Fig. A.4 a) retractable beam to which the receiver array frame is bolted, b) attaching the measurement wheel at rear of truck

2. A cable (see Fig. A.4a) from the truck-bed workstation is then connected to the central connection box (Fig. 3.6a).
3. Power to the receiver array as well as to the ETI master control unit is provided by connecting two wires in the truck-bed workstation unit (Fig. A.5).

Fig. A.5 a) Electronics enclosure with ETI master control unit, attached to truck-bed workstation, b) Schematic of connection external to the truck-bed workstation

A.4 The data acquisition computer

1. For extended operation, the data acquisition notebook computer should be plugged into the inverter box (Fig. A.5a) in the workstation, and the inverter box is switched on.
2. Two connections are provided to the computer (Fig. A.5a). The RS-232 plug transmits the HEXAMITE data, and is directly attached to the RS-232 port on the computer. The USB plug transmits the ETI data, and is plugged into the computer's USB port.

The above completes the connections for the entire system. A schematic of the connections external to the truck-bed workstation is shown in Fig. A. 5b. The ETI system (sonar, stage sensor, and wheel) can be operated independently of the HEXAMITE system, and vice-versa, and so can be tested independently. Although the entire assembly can be (and has been) done by a single person (see Fig. A.2), attaching the

stainless steel pipe extension is more easily performed by a two-person team. Depending on how the receiver array is stored, whether the assembly is done by one or two persons, and the experience of those involved, assembling the entire system can probably be done in less than 30 minutes. The reverse process is used to dismantle the assembled system. The time for disassembly will depend on the same factors, and should be comparable to that for assembly.

B. Using the data acquisition software

The data acquisition software was developed with the aim of making its use as simple and as robust as possible. The software design therefore sought to minimize operator input, relying as much as possible on a point-and-click operation. It has also been designed that the view or what the operator needs to do follows a sequential pattern, as will become apparent.

B.1 Preliminary steps to data acquisition

The initial view when the program starts up (Fig. B.1a) deals with the bridge site to be studied. This part of the program is linked to a database (actually in its current form, the same database as that used in the Web application) with location and other bridge characteristics. Here the operator can type in the stream (feature intersected), e.g., Tippecanoe River, and the route name (facility carried), e.g., SR 18. If either the ENTER or the Find button is pressed, then the database is searched with these entries, and the results are displayed. In fact, if only one of these is known and is entered, then the database is searched, but will generally return multiple possibilities. These names need to be entered in exactly the same form as it exists in the database. If these are not known, then drop-down lists can be used to select from the list of available entries rather than being typed in. If incorrect entries are typed in, then an error message will appear. All of the information in the database resulting from this search is available to the operator by using the horizontal or vertical scrollbar. If multiple bridges (usually at most two) correspond to the stream and route, then selection by the third criterion, the NBI number (or the corresponding drop-down list) can be used. The selection of the appropriate bridge site is important for subsequent work, since all of the data that has already been obtained, or will be obtained, are stored under the NBI number corresponding to the bridge. Once the bridge has been selected, the Confirm button is pressed, and the subsequent view (Fig. B.1b, which shows a partial view in which the bottom two-thirds of the view which contains nothing of relevance has been omitted) appears, which deals with file management. The information box to the bottom left was intended primarily for debugging purposes; it may be ultimately removed or retained.

The default file folder corresponding to the selected bridge is shown. Note that informational boxes are colored as light blue, while boxes where information need to entered are in white. Option buttons to the right give the option of either collecting data or analyzing data. Collect would be selected if measurements are to be made, while analyze would be selected if data have already been collected and are to be analyzed. If collect is chosen by clicking on it, the file name to be used to store the data appears. The file name comprises an initial text, which is the date, followed by an underscore. A choice is then given depending on whether the measurement is to be made on the upstream side (default, UP) or the downstream side (DN) of the bridge, followed by another underscore, terminated by a two-digit number, which is associated with a run number. This allows multiple (up to 99) datasets to be collected on the same day of a site measurement on the same side of a bridge. After each measurement, the run number is automatically incremented by 1, so that each new measurement will be stored in a different file. If the file name is accepted, then the checkbox to the right of the name should be checked. What happens when the analyze option is chosen will be dealt with below ins Sec. B.3.

After the filename checkbox has been checked, a new view (Fig. B.1c, again a partial view) appears that prompts for information. Reference locations are used to determine the 'global' coordinates. The HEXAMITE system provides locations relative to a local origin defined on the frame of the receiver array. The measurement wheel also gives distance along the bridge only from the point where the wheel was placed. Neither of these coordinate systems may be of direct physical interest. The operator can enter more meaningful coordinates, which are the coordinates of the local origin at

the beginning of traverse (the first column) and at the end of the traverse (second column). If a reproducible mapping of the results is not desired, then these can be left blank (as on Fig. B.1e), and the results will then be available only in terms of the local and wheel coordinates. It is also possible to enter the locations of bridge piers (this is not essential, and is used only for plotting purposes – this is not yet implemented).

The other important information that needs to be entered is, under default operation, the ambient air temperature in °F. This is used in the determination of a conversion factor relating the time for an acoustic signal to travel from transmitter to receiver to the distance between the transmitter and receiver. An option is given to perform an on-site calibration, but this is rather cumbersome and time-consuming, and therefore is not described in this report. Once the air temperature is entered, then the checkbox to the right should be checked for confirmation in order to bring up the next view (Fig. B.1e). A simple check on whether the air temperature is within a reasonable range is made – the value entered must be between 32 and 110, or an error message is generated.

B.2 The data acquisition step: Test and Record modes

After the temperature has been entered, and the checkbox checked for confirmation, the main data acquisition view (Fig. B.1d) appears. The data acquisition basically involves the process by which raw data from the ETI system and/or the HEXAMITE system are transmitted back to the computer, processed in quasi-real time to obtain more directly interpretable information, e.g., the distances measured by the HEXAMITE system are converted into local spatial coordinates of the transmitters, and displayed graphically to provide immediate feedback to the operator. Data acquisition may be performed in either a TEST mode or a RECORD mode, with the main difference being that, in the TEST mode, the data are not stored permanently on the hard disk. It is intended to be used as a preliminary step before taking actual measurements, during which the operator can optimize the aim of the transmitters if necessary or otherwise check that all necessary system components are functioning properly.

Testing can be done separately on the ETI (Sonar) subsystem, or the HEXAMITE (pos'n) subsystem, or both together at the same time, by checking the appropriate check box. This option can be useful in troubleshooting. The initial default is that only the Sonar subsystem is to be tested. This allows an initial measurement with the stage sensor to be performed, which is then used for pre-aiming the transmitters while these are still on the bridge deck. As noted in Chapter 4, setting the appropriate angle with respect to the vertical of the transmitters is essential for the proper functioning of the HEXAMITE system. To the right in the Data collection frame, just below the main buttons, the operator can enter the approximate working horizontal distance (dist) of the crane/stainless steel pipe extension from the receiver array (10-ft is the default, but this can be changed by the operator). Pressing the Test collection button begins the data acquisition process. The acquired data, such as the sonar and stage values, should appear in the appropriate boxes (Fig. B.1e – note that the results shown in Fig. B.1e are simulated from previously acquired data, which also explains the Simulate data collection button to the lower left above the debugging information box – the box at the lower left with only white space) as they are received. Simultaneously, the sonar and stage values are plotted (as negative values, Fig. B.1e). In the plotting, it is assumed that the submergence of the sonar is zero, i.e., the sonar reading is plotted directly below the stage reading.

Attention should be paid to the numerical values as they appear. If a value is consistently zero, or is unreasonably large, then this may mean that the component is not responding properly, e.g., because it is not connected. On the other hand, if the truck is stationary, or if the sonar is not deployed, then zero or other unrealistic but explainable values may appear. Unrealistic but explainable values may

also lead to one or more of the curves not appearing in the figure. Another notable feature is the value inset into the graph. This is the maximum sonar value that has been observed until that instant, which may be useful immediate information when looking for evidence of scour.

When the Test collection button is pressed, it toggles to an END Test button, which can be pressed anytime. Thus, after assembling the system, driving the truck to the start of the traverse, and extending the retractable beam with the ETI sensor over the side of the bridge, the operator will run a test of the ETI system in order to determine the appropriate angle at which to set the transmitters. After the transmitter angle has been set, the scour sonar and transmitters could then be deployed, at which point another test of the ETI system could be performed to check the operation of the sonar. If desired, the operation of the measurement wheel can also be checked, even with a stationary truck by manually turning the wheel during a test.

After the test of the ETI subsystems, the test of the HEXAMITE system can be performed by checking the appropriate box (pos'n). The ETI system box (sonar) can be left checked or unchecked. Pressing the Test button again starts the data acquisition, and acquired data values, the spatial coordinates of the top and bottom transmitters, as well as of the probed point (labeled Sonar), should begin to appear in the appropriate boxes. It is emphasized that the values appearing have not undergone the pre-screening process, and therefore are 'raw' values, and it is left to the operator to interpret whether the raw results are of sufficiently high quality. Additional guidance is given by the two sets of four colored circles to the right with values just below each set. Each set corresponds to a transmitter-receiver pair, so that the top set indicates the four receivers paired with the top transmitter, and the bottom set the four receivers paired with the bottom transmitter. Each circle is color-coded to indicate the quality of the 'raw' data, which is evaluated by only the first level of prescreening, i.e., based solely on the transmitter-receiver distances (see Appendix C for details regarding pre-screening of data). A green color implies 'good' data quality, while 'red' implies 'poor' quality. The values indicate the percentage of data from each transmitter that satisfy the first level of pre-screening criteria. Experience indicates that, for a stationary truck, percentages in excess of 90% should be readily achievable as shown in Fig. B.1f (as noted above, the results in these views are simulated after the fact rather than during an actual field site visit – Fig. B.1i shows a picture of the notebook screen, with an earlier version of the software, during a field study). In contrast to the colored circles and the numerical values, the graphs of the probed points determined from the HEXAMITE measurements are based on pre-screened values. With a stationary truck, the x - y and x - z plots should exhibit a relatively compact shape (as seen in Fig. B.1f and also in Chapter 4). A final data item that might be useful is an indication of the degree of submergence of the sonar, estimated from the measured HEXAMITE data. This should be in the range of 1-ft, though because of measurement uncertainty could exceed 2-ft.

Once the operator is satisfied that the entire scour-monitoring system is operating as expected, testing can be stopped and the next phase started by checking the checkbox just to the right of Test collection button. This brings up the START collection button (not shown in any of the following screenshots), which is pressed to acquire data that will be recorded, i.e., stored on disk. Exactly the same information is provided by the interface in the RECORD mode – as noted before, the main difference between the TEST and the RECORD mode is that in the latter the data are stored on disk. A (simulated) result is shown in Fig. B.1g. A feature that may be useful is a Pause button (to the right of the START collection button, again not shown in the screenshots), which will suspend recording of data until it is toggled again. If measurements need to be suspended for some brief time, e.g., to avoid debris, then the Pause button can be pressed, the scour sonar withdrawn temporarily, and then after re-deployment, the Resume (which is the toggled version of the Pause) button can be pressed to resume operation. For an extended stoppage of measurement, it may be preferable to stop the process entirely,

which is done by pressing the CLOSE file button (to the bottom middle right), which will automatically bring up the next view and at the same time remove the other elements of the user interface from view (Fig. B.1h – this does not show the initial view, but rather a partial view of the results after the PLOT data button has been pressed), where graphical analysis of the results can be performed.

B.3 Graphical analysis of results

All of the files at a given site for which data have been stored are available for plotting. The default is the most recently collected data, but options include all of the data taken on the most recent day of data collection, or all of the data without exception. Specific files can then be selected using the list box to the right. The operator could also choose not to plot results and simply collect another set of data, by selecting the Collect option again, and starting the collection process over again. Alternatively, if data have already been collected, then selecting the analyze option will skip entirely the data collection views, and bring up the plotting facility.

Various options for plotting the results are available by checking the appropriate checkbox. The default option is that only the fully post-processed (filtered – see Appendix C for a discussion of filtered data) data are plotted. Other options include raw (which actually means pre-screened), cleaned (which refers to a data set resulting after points that vary too quickly, namely, spikes, have been removed), and sonar (which refers to an estimate based on stage-sensor plus sonar reading, and an assumed level of sonar submergence, currently set at 0.7 ft). Several options may be selected at the same time – in Fig. B.1h, the raw and filtered data are plotted together with the sonar data, allowing quick comparison.

An End button (bottom right) is provided to close the entire application.

B.4 Further comments

The above describes the current stage of development of the user interface for the data acquisition software. It should be noted that development continued after the last field visit (reported above, on 17 Feb. 2009) with the expectation that further field work would be done. As such, some aspects of the software are more thoroughly tested than others. Also some features of the software are intended for demonstration or instructional purposes, e.g., simulating data acquisition and analysis, or for debugging, and these may eventually be removed. One important facility that was planned, but in the end, not yet implemented, is a report-generation facility that would generate a WORD document, summarizing the results of data collection and analysis at a given site. A further enhancement might include an automatic measurement of temperature (and possibly humidity), so as to avoid operator error in entering temperature values.

Fig. B.1 a) initial view of data acquisition software, showing the bridge database search facility, b) partial view showing the file management facility, c) partial view showing the inputs for locating the truck on the bridge (bridge coordinates) and input for temperature for calibration

Fig. B.1 d) view showing the facility to test data acquisition (the initial default view), e) the results of testing only the ETI system (note numerical values in boxes and curves in uppermost graph)

Fig. B.1 f) (simulated) results of testing the HEXAMITE system (stationary), g) (simulated) results of a recorded measurement (moving truck)

Fig. B.1 h) facility for graphical analysis of results (postprocessed results compared with raw results compared with estimated sonar results), i) notebook in the field with an earlier version of the user interface

C. Details of the Scour-Monitoring Visual Basic program

C.1 Calibration of the HEXAMITE system

Because its basis is acoustic, the accuracy of the HEXAMITE positioning system will vary with the calibration of the system to ambient conditions. The speed of sound depends principally on temperature, but also to a more limited extent on other conditions, such as humidity and wind conditions. Further, due to the relatively short distances being measured, the electronic characteristics of the HEXAMITE units, e.g., in the timing circuit, might also play a role. The most accurate results would be obtained by repeated calibrations on site, since ambient conditions may change over the course of field site survey. Nevertheless, performing a calibration is not a straightforward exercise, and it was decided that, in the interest of a simpler operation, the default would incorporate only a temperature-dependence. In the present version of the data acquisition program, therefore, a full calibration option is available, but the default requires only that the operator input the ambient temperature in °F. A pre-calibration to take care of any HEXAMITE electronic characteristics is assumed to have previously been performed. Whenever there is a change in the acoustic transmitter/receiver, or a HEXAMITE control unit, a re-calibration should be performed to obtain the calibration offsets (see discussion below), but this should not be a routine operation.

C.2 Temperature-calibration equation and determining distances

The temperature, T , in °F is read from the Visual Basic form, and a temperature-dependent calibration coefficient is evaluated as

$$C_T = \frac{C_{T0}}{f_m} \times \sqrt{1 + \frac{(T - 32)/1.8}{273.15}} \quad (0.1)$$

where $C_{T0} = 331.3$ m/s is the speed of sound at an air temperature of 32°F, and $f_m = 500$ kHz is the frequency of the HEXAMITE timing circuit. The distance, L , (in mm) from a transmitter to a receiver is then calculated from

$$L = C_T \times (N_H - N_{H0})$$

where N_H is the number of pulses (measuring the time taken for the acoustic signal emitted from the transmitter to reach the receiver) and N_{H0} is a pre-calibrated offset depending only on the HEXAMITE electronics. Thus, N_{H0} should be recalibrated each time a transducer or HEXAMITE unit is changed.

C.3 Determining transmitter coordinates

To determine the three spatial coordinates, (x_t, y_t, z_t) , of a transmitter, three equations are necessary, and hence at least three receivers, the spatial coordinates of which are known, must be available. If the receiver coordinates are denoted by (x_{ri}, y_{ri}, z_{ri}) , $i=1,2,3$, then the three equations may be expressed as

$$\begin{aligned} L_1^2 &= (x_t - x_{r1})^2 + (y_t - y_{r1})^2 + (z_t - z_{r1})^2 \\ L_2^2 &= (x_t - x_{r2})^2 + (y_t - y_{r2})^2 + (z_t - z_{r2})^2 \\ L_3^2 &= (x_t - x_{r3})^2 + (y_t - y_{r3})^2 + (z_t - z_{r3})^2 \end{aligned} \quad (0.2)$$

where L_1, L_2, L_3 are the three distances from the transmitter to the three receivers. Such a nonlinear system of three equations in three unknowns is solved by a standard Newton-Raphson technique. As noted before, because the actual configuration uses four receivers, four sets of three-equations systems are actually solved, and the average solution is reported. The spatial coordinates of both transmitters are determined in the same way.

C.4 Determining the coordinates of the probed point on the streambed

The ultimate goal of the positioning system is not determining the spatial coordinates of the transmitters, but rather the spatial coordinates of the point on the streambed being probed by the scour sonar. This requires combining the information regarding the distance to the streambed as measured by the scour sonar, the spatial coordinates of both transmitters, and the position of transmitters relative to the scour sonar transducer. For simplicity, the transmitters and the sonar scour transducer are assumed to lie on a straight line, thereby neglecting the small offset in position between them. This permits using the principle of similar triangles to determine the location of the probed point. If the distance between the transmitters is denoted as l_t ($= 946 \text{ mm} = 37.25 \text{ in}$), the distance from the top transmitter to the sonar scour transducer as l_s ($= 1797 \text{ mm} = 70.75 \text{ in}$), and the distance to the streambed measured by the scour sonar is l_b , then the coordinates of the probed point may be evaluated as

$$\begin{aligned}x_{bed} - x_{tt} &= b \times (x_{tt} - x_{tb}) \\y_{bed} - y_{tt} &= b \times (y_{tt} - y_{tb}) \\z_{bed} - z_{tt} &= b \times (z_{tt} - z_{tb})\end{aligned}$$

where $b = (l_s + l_b) / l_t$ is the ratio of the sides of similar triangles, and (x_{tt}, y_{tt}, z_{tt}) and (x_{tb}, y_{tb}, z_{tb}) are the coordinates of the top and the bottom transmitters. The neglected offset does incur an error that is estimated to on the order of 0.25 ft. An inconsistency might be pointed out, in that the real separation distance ($= 37.25 \text{ in}$) between the transmitters is used in evaluating the factor b , not the separation distance that would be inferred from the HEXAMITE measurements. It was checked that the latter is generally within 15% of the real separation distance, and its use in evaluating b could exacerbate the scatter in the inferred location of the probed point.

C.5 Data screening and filtering

The raw data from HEXAMITE positioning system can be noisy, and some initial data screening is performed in order to immediately remove data that are evidently unreliable. The following conditions will lead to data from the HEXAMITE units being immediately discarded:

- If the number of pulses for any transmitter-receiver pair (time for the sound signal to travel from the transmitter to the receiver) is reported as being less than a certain value (currently set at 3000) or the absolute difference in number of pulses between the top transmitter and the bottom transmitter for the same receiver is greater than a certain value (currently set at 2000). These conditions on the measured distance (the first-level of pre-screening) basically sets a minimum measured distance of $\approx 6 \text{ ft}$, and the maximum difference in distance between top and bottom transmitters to a given receiver to be 4 ft. This first-level of pre-screening operates at the basic level of measured distances, and is used in a preliminary assessment of signal quality (in the user interface of the data acquisition software).
- if the distance in the x -direction, i.e., perpendicular to the plane of the array, is less than a specified amount (currently set at $450 \text{ mm} \approx 1.5 \text{ ft}$) or more than a specified amount (currently

set at 4800 mm $\approx$ 16 ft) – a typical operating distance is expected to be between 8 ft and 12 ft or if the horizontal distance between the top and the bottom transmitters is greater than a certain amount (currently set at 450 mm $\approx$ 1.5 ft), or the difference in elevation of the top and bottom transmitters is greater than a certain amount (currently set at 600 mm $\approx$ 2 ft) – this condition currently restricts the measured tilt of the transmitters to be less than 30° relative to the vertical. This is the second and final level of pre-screening that operates on the determined spatial coordinates of the transmitters.

The above conditions, which are not particularly stringent, may be considered as pre-processing criteria for eliminating data to be recorded; they do not guarantee that the retained data are noise-free. The above pre-screening conditions are applied only to the transmitter measurements.

Because the retained data and especially the thereby inferred locations of the probed point may still contain unrealistic spikes and fluctuations, a post-processing filtering operation on the coordinates of the probed point is also undertaken as a default (the raw retained data after the initial data screening are always available). The post-processing is applied only to the 'bed' (not the transmitter) coordinates. The post-processing filtering consists of two phases. Firstly, if a large change in horizontal coordinates (currently set as a horizontal distance of 2 ft) occurs immediately before and immediately after a point, then the point is flagged and omitted. Secondly, a centered moving average is taken over a specified number (currently set at five) of measurement points. As seen in the reported tests, the resulting data series is considerably smoothed by these operations, and allows a more realistic interpretation of the streambed profile.

D. Additional details of the Web Application software

Two suites of software routines were developed to support the Web-based flood information tool, one, written in PERL, to convert the raw USGS data files to the XML files that serve as input to the other, written in FLASH, that display the data and provide the graphical web interface for the user. The following gives some details of both series of routines that might be useful if substantial changes are being considered. All of these routines, together with sample data files, will be placed on a CD-ROM, and therefore made available.

D.1. Routines for XML conversion

The raw data files from USGS are received soon after the hour, and a UNIX (cron) script is run every hour at 20 minutes after the hour to process the incoming files, i.e., to perform the XML conversion and then to move the raw files to temporary storage. Approximately 140 files covering approximately 100 gaging stations are processed. A station will generally report gage height information (in a file with a .GH extension), but may also report discharge data (in a separate file with a .D extension). The name of each file follows the format, X.Y.Z.ext, where X is the USGS station number, Y is the date, and Z is the time in 24-hr format. Each file contains not only the latest available data, but also data from the previous approximately 24 hours. The contents and format of a typical gage height file (gage height data, 03335500.20100216.1505.GH for station 03335500 – the Wabash River at Lafayette, for date 2/16/2010, at time 15:05) are shown in Fig. D.1. After lines of comments and headings, the gage heights starting from 2/15/2010 at time 16:00:00 EST are given (at the starting time, the gage height is 3.53 ft), each line for a separate time, until the most recent time available on date 2/16/2010 at time 13:00:00 EST (at the ending time, the gage height is 3.48 ft). These data are converted to XML (see the extract of the resulting XML datafile, mastermerge.XML, in Fig. D.2), and all such data from all stations are aggregated into a single XML file (mastermerge.XML) containing the ‘current’ (i.e., for the previous approximately 24 hours) gage height data for all stations. In the XML file, for each defined station, a line defines the station (station id, num, and name) and is followed by lines of data (with date, time, and value), and terminates with a closing delimiter (</station>). A similar operation is also applied to files containing discharge data, resulting in an analogous XML file for discharge data, also named mastermerge.XML but located in a different directory (folder).

All of the stations (145 in total) defined in the display routines must be included in the XML file, and must follow the order that they have been defined in these routines (the num data item in the XML file is an index used in the display routine to refer to the station). If there is no current data available for a station, then the station is still defined in the XML file, but there would be no lines of data following the definition, e.g., as in Fig. D.3.

The Perl scripts The basic routines for processing the incoming data files and producing the ‘current’ XML data files are contained in the *processgs.pl* file. It reads the list of USGS gaging stations defined in the display routines from a file named *hashfile.txt* (an extract from which is shown in Fig. D.4). Each line of *hashfile.txt* contains the station number, an index number defined in the display program, and the station name, all of which are needed for the XML files. The PERL script then processes in turn all of the incoming gage height (.GH) files, and then all of the incoming discharge (.D) files. A first routine *findlastfiles()* determines the most recent files for each station. Normally this would not be necessary because the usual case would be that the folder contains only the most recent files. Under certain

circumstances, when other routines that should have transferred old data files to temporary storage have not terminated successfully, old data files may still reside in the folder, and so should not be processed to give the 'current' data. The actual conversion is performed by the routine *processdata()*, which reads the most recent file for each station, extracts the data from the raw data file, and saves these in memory. When all of the files have been read, then the data, if available for a station, are written out in XML format to the output file, named *mastermerge.XML*.

The routines for processing the files to produce the daily archived data file are contained in the file *processgsd.pl*, and share much in terms of structure with those routines for the current data files. They operate on files in a temporary file storage folder that may contain files that are two or more weeks old. The main difference is that the relevant data for a given station are not necessarily contained within a single raw data file, because the data may not be updated frequently, and so the relevant data may be contained within two rather than one files. Note that the program to archive the daily data for the previous day is run once per day (currently at 9:20 am), and so assumes that any updates with data from the previous day is available by the time that the program is run. It therefore queries all files that are in the temporary storage folder for relevant data, skipping those files for which a daily archived file has already been produced, and in the end producing a daily archived file stored in a separate subfolder. An extract from the daily archived gage height XML file for a given station is shown in Fig. D.5.

If gaging stations are to be added to the display, then the file with the station definitions (*hashfile.txt*) will need to be modified. The additional stations should be defined and placed in exactly the same order as they are defined in the display program. The total number of stations in the PERL scripts will also need to be changed. No other change should be necessary. Removal of gaging stations can be similarly accomplished, though the alternative of simply not displaying removed stations might be considered as a more convenient solution, since it would require only changes in the display program and not in the PERL scripts.

D.2. Routines for data display and web interface

The program to manage the web interface and display the data was originally written in Macromedia FLASH 6 (now Adobe FLASH) by Jeremy White; the version that is currently running include some bug fixes and minor enhancements by the PI, and is contained in the file, *floodstageviewer-dbridge fla*. Unlike PERL script, which might be considered a classical programming language that would be intelligible to those familiar with general programming, working with FLASH and the associated ActionScript requires familiarity not only with FLASH programming but with the programming environment, provided by the FLASH software. The following cannot introduce this environment and hence will be limited to pointing out elements that are of direct interest in modifying the code, and also assumes some familiarity with FLASH.

```

# //UNITED STATES GEOLOGICAL SURVEY    http://water.usgs.gov/
# //NATIONAL WATER INFORMATION SYSTEM  http://water.usgs.gov/data.html
# //DATA ARE PROVISIONAL AND SUBJECT TO CHANGE UNTIL PUBLISHED BY USGS
# //RETRIEVED: 2010-02-16 15:06:02
# //FILE TYPE="NWIS-I UNIT-VALUES" EDITABLE=NO
# //DATABASE NUMBER=1 DESCRIPTION=" Standard data base for this site."
# //STATION AGENCY="USGS " NUMBER="03335500 " TIME_ZONE="EST" DST_FLAG=N
# //STATION NAME="WABASH RIVER AT LAFAYETTE, IN"
# //LOCATION NUMBER=0 NAME="Default"
# //DD DDID=" 2" RNDARY="2223456782" DVABORT=120
# //DD LABEL="Gage height (DCP ID: CE6D361C) (ft)"
# //PARAMETER CODE="00065" SNAME="Gage height"
# //PARAMETER LNAME="Gage height, feet"
# //TYPE CODE=C NAME=COMPUTED
# //RANGE START="20100215150500" END="20100216150500" ZONE="LOC"
DATE  TIME  TZCD  VALUE  PRECISION  REMARK  FLAGS QA
8D    6S    6S    16N    1S    1S    32S    1S
20100215    160000 EST    3.53    3                W
20100215    170000 EST    3.51    3                W
20100215    180000 EST    3.49    3                W
20100215    190000 EST    3.47    3                W
20100215    200000 EST    3.45    3                W
20100215    210000 EST    3.42    3                W
20100215    220000 EST    3.38    3                W
20100215    230000 EST    3.33    3                W
20100216    000000 EST    3.27    3                W
20100216    010000 EST    3.23    3                W
20100216    020000 EST    3.19    3                W
20100216    030000 EST    3.17    3                W
20100216    040000 EST    3.19    3                W
20100216    050000 EST    3.23    3                W
20100216    060000 EST    3.28    3                W
20100216    070000 EST    3.33    3                W
20100216    080000 EST    3.38    3                W
20100216    090000 EST    3.41    3                W
20100216    100000 EST    3.43    3                W
20100216    110000 EST    3.45    3                W
20100216    120000 EST    3.47    3                W
20100216    130000 EST    3.48    3                W

```

Fig. D.1: Sample raw USGS gage height data file (03335500.20100216.1505.GH) for station 0333550 (Wabash River at Lafayette, IN) transferred just after 3:00 pm on 2/16/2010.

```

<station id='03335000' num = '39' Name = 'WILDCAT CREEK NEAR LAFAYETTE, IN'>
<sample date='20100215' time='160000' value='3.64'/>
<sample date='20100215' time='170000' value='3.71'/>
<sample date='20100215' time='180000' value='3.73'/>
<sample date='20100215' time='190000' value='3.68'/>
<sample date='20100215' time='200000' value='3.61'/>
<sample date='20100215' time='210000' value='3.76'/>
<sample date='20100215' time='220000' value='3.71'/>
<sample date='20100215' time='230000' value='3.74'/>
<sample date='20100216' time='000000' value='3.65'/>
<sample date='20100216' time='010000' value='3.79'/>
<sample date='20100216' time='020000' value='3.72'/>
<sample date='20100216' time='030000' value='3.77'/>
<sample date='20100216' time='040000' value='3.79'/>
<sample date='20100216' time='050000' value='3.75'/>
<sample date='20100216' time='060000' value='3.74'/>
<sample date='20100216' time='070000' value='3.75'/>
<sample date='20100216' time='080000' value='3.67'/>
<sample date='20100216' time='090000' value='3.70'/>
<sample date='20100216' time='100000' value='3.73'/>
<sample date='20100216' time='110000' value='3.58'/>
<sample date='20100216' time='120000' value='3.69'/>
<sample date='20100216' time='130000' value='3.66'/>
<sample date='20100216' time='140000' value='3.73'/>
</station>
<station id='03335500' num = '40' Name = 'WABASH RIVER AT LAFAYETTE, IN'>
<sample date='20100215' time='160000' value='3.53'/>
<sample date='20100215' time='170000' value='3.51'/>
<sample date='20100215' time='180000' value='3.49'/>
<sample date='20100215' time='190000' value='3.47'/>
<sample date='20100215' time='200000' value='3.45'/>
<sample date='20100215' time='210000' value='3.42'/>
<sample date='20100215' time='220000' value='3.38'/>
<sample date='20100215' time='230000' value='3.33'/>
<sample date='20100216' time='000000' value='3.27'/>
<sample date='20100216' time='010000' value='3.23'/>
<sample date='20100216' time='020000' value='3.19'/>
<sample date='20100216' time='030000' value='3.17'/>
<sample date='20100216' time='040000' value='3.19'/>
<sample date='20100216' time='050000' value='3.23'/>
<sample date='20100216' time='060000' value='3.28'/>
<sample date='20100216' time='070000' value='3.33'/>
<sample date='20100216' time='080000' value='3.38'/>
<sample date='20100216' time='090000' value='3.41'/>
<sample date='20100216' time='100000' value='3.43'/>
<sample date='20100216' time='110000' value='3.45'/>
<sample date='20100216' time='120000' value='3.47'/>
<sample date='20100216' time='130000' value='3.48'/>
</station>

```

Fig. D.2: Extract from XML file (mastermerge.XML) for the most recent data, including the data based on the raw data file 03335500.20100216.1505.GH, generated by the PERL script. Note that the results from another station 00333500 are also shown.

```

<sample date='20100216' time='143000' value='3.80'/>
<sample date='20100216' time='144500' value='3.80'/>
</station>
<station id='04177810' num = '124' Name = 'FISH CREEK NEAR ARTIC, IN'>
</station>
<station id='04178000' num = '125' Name = 'ST. JOSEPH RIVER NEAR NEWVILLE, IN'>
<sample date='20100215' time='151500' value='5.01'/>
<sample date='20100215' time='153000' value='5.01'/>

```

Fig. D.3: Extract of a 'current' mastermerge.XML file showing a gaging station (04177810, Fish Creek near Artic. IN) with no data available – this station seems to be no longer operating.

```

03274650:1:WHITEWATER RIVER NEAR ECONOMY, IN
03275000:2:WHITEWATER RIVER NEAR ALPINE, IN
03275600:3:EAST FORK WHITEWATER RIVER AT ABINGTON, IN
03276000:4:EAST FORK WHITEWATER RIVER AT BROOKVILLE, IN
03276500:5:WHITEWATER RIVER AT BROOKVILLE, IN
03291780:6:INDIAN-KENTUCK CREEK NEAR CANAAN, IN
03294000:7:SILVER CREEK NEAR SELLERSBURG, IN
03302220:8:BUCK CREEK NEAR NEW MIDDLETOWN, IN
03302680:9:WEST FORK BLUE RIVER AT SALEM, IN
03302800:10:BLUE RIVER AT FREDERICKSBURG, IN

```

Fig. D.4: Extract (first ten lines) from hashfile.txt, which lists the USGS gaging stations defined in the display program, and for which XML data are generated by the PERL routines

The data input to the program is contained in three sets of XML files, i) the first (in a file, scour.XML) specifying the characteristics of the bridges that are defined as scour critical (see Fig. D.6), ii) the second (in file floodPointers.XML) defining the flood stage at a stream gaging site (see Fig. D.7), if available, and iii) the third, already discussed in the previous section, containing the USGS stream gaging data. Both the first and the second are assumed to be relatively static, in that they may be updated every year or even every few years, while the third is quite dynamic, with hourly updates produced by the PERL scripts described in the preceding subsection from the raw USGS files. While the various map overlays were obtained from ARCGIS files, quantitative spatial information was not retained for use with the FLASH routines, and because of the relatively static nature of the gaging site and bridge locations, the original developer opted to create, define and place manually the graphical display (FLASH) elements associated with these sites and locations. Unless a means for accessing quantitative spatial information is implemented in the FLASH routines, the addition of new gaging sites and bridge locations would also require manual definition and placement at individual sites.

Using the Movie Explorer in the FLASH programming environment, the various ActionScripts can be explored conveniently by selecting the Show ActionScript button. The two most important are

- AS Main and Gauge: Frame 15 (XML/Create Windows) – reads in the gage height, discharge, and floodstage XML files. and creates the initial web page view,
- AS Scour Frame 12 (Load scour) – reads in the scour-critical bridge information and prepares the display of the bridge information,

and will need to be modified if new gaging sites and bridge locations are to be added. At the very least, the hard-coded number of sites (145) or locations (203) will need to be changed. If gaging sites or

bridge locations are to be removed, then the possibility of dealing with this through simply not displaying these sites or locations in the display software might be considered. This might minimize or obviate entirely the need to modify the XML datafiles and hence the other software (PERL) routines.

```
<station id='03335500' num = '40' Name = 'WABASH RIVER AT LAFAYETTE, IN'>
<sample date='20100216' time='000000' value='3.27'/>
<sample date='20100216' time='010000' value='3.23'/>
<sample date='20100216' time='020000' value='3.19'/>
<sample date='20100216' time='030000' value='3.17'/>
<sample date='20100216' time='040000' value='3.19'/>
<sample date='20100216' time='050000' value='3.23'/>
<sample date='20100216' time='060000' value='3.28'/>
<sample date='20100216' time='070000' value='3.33'/>
<sample date='20100216' time='080000' value='3.38'/>
<sample date='20100216' time='090000' value='3.41'/>
<sample date='20100216' time='100000' value='3.43'/>
<sample date='20100216' time='110000' value='3.45'/>
<sample date='20100216' time='120000' value='3.47'/>
<sample date='20100216' time='130000' value='3.48'/>
<sample date='20100216' time='140000' value='3.48'/>
<sample date='20100216' time='150000' value='3.48'/>
<sample date='20100216' time='160000' value='3.48'/>
<sample date='20100216' time='170000' value='3.48'/>
<sample date='20100216' time='180000' value='3.48'/>
<sample date='20100216' time='190000' value='3.47'/>
<sample date='20100216' time='200000' value='3.46'/>
<sample date='20100216' time='210000' value='3.44'/>
<sample date='20100216' time='220000' value='3.43'/>
<sample date='20100216' time='230000' value='3.41'/>
</station>
```

Fig. D.5: Extract of a daily archived gage height XML data file (for station 03335500) showing the data provided to the display program

```

<?xml version="1.0" encoding="UTF-8" standalone="yes"?>
<Root>
  <Row Bridge_id="30 (001-15-01300A)" District_code="5 (15)" Facility_carried="SR 1 (7.16 S I-
74)" Features_inter="BRUSHY FORK" Total_num_piers="2" Num_piers_in_water="1"
Type_service_under="5" Scour_rating="2"/>
  <Row Bridge_id="460 (001-02-01854)" District_code="2 (2)" Facility_carried="SR 1 (6.68 N I-
69)" Features_inter="CONRAD DITCH" Total_num_piers="2" Num_piers_in_water="2"
Largest_vert_dist="0106" Type_service_under="5" Scour_rating="2"/>
  <Row Bridge_id="470 (001-02-01855)" District_code="2 (2)" Facility_carried="SR 1 (9.07 S
SR 8)" Features_inter="WATSON DITCH" Total_num_piers="2" Num_piers_in_water="2"
Largest_vert_dist="0124" Type_service_under="5" Scour_rating="2"/>
  <Row Bridge_id="1590 (005-57-06111)" District_code="2 (57)" Facility_carried="SR 5 (1.08 N
US 6)" Features_inter="ELKHART RIVER" Total_num_piers="4" Num_piers_in_water="2"
Largest_vert_dist="0169" Type_service_under="5" Scour_rating="3"/>

```

Fig. D.6: Extract (first few lines) from the file myscour-rev.XML providing data for the defined scour-critical (as of 2005) bridges.

```

<?xml version="1.0" encoding="utf-8" ?>
<points>
  <station id ="03274650" num ="1" flood = "7.0">
  </station>
  <station id ="03275000" num ="2" flood = "17.0">
  </station>
  <station id ="03275600" num ="3" flood = "15.0">
  </station>
  <station id ="03276000" num ="4" flood = "99999">
  </station>
  <station id ="03276500" num ="5" flood = "20.0">
  </station>

```

Fig. D.7: Extract (first few lines) from the file floodpointers.XML, which provides the NOAA defined flood stages for each defined USGS gaging station, when available (if a flood stage is not defined for a given station, it is still listed, but a value of 99999 is given, as in station 03276000)