ERDC/RSM-TN-10, January 2004
Regional Sediment Management (RSM) Demonstration Program Technical Note

US Army Corps of Engineers®
Engineer Research and Development Center

Local-Scale Technologies for Measuring and Monitoring Sediment Process

PURPOSE

This technical note presents the results of the Regional Sediment Management (RSM) Research Program technical workshop conducted in Mobile, AL, 21-22 May 2002. The purposes of the workshop were to identify information and data needs and appropriate technologies for gathering such needs to include existing and emerging technologies at a variety of spatial and temporal scales for supporting RSM.

BACKGROUND

One of the topic areas in the RSM Research Program is "Measuring and Monitoring Sediment Process," which focuses on evaluating and adapting new technologies for ascertaining sediment transport and yield on regional scales to support RSM. To determine what current and emerging technologies are available to support RSM, one must determine the key users and vendors of these technologies and their current applications. As part of the overall objectives of the Measuring and Monitoring Sediment Process research effort, a technical workshop was conducted to (1) identify the major end users, (2) identify and define RSM measurement needs, and (3) identify existing and emerging measuring and monitoring technologies that best support RSM.

The technical workshop was set up as a joint effort between the Local- and Large-Scale work units within the RSM Measuring and Monitoring Sediment Process focus area with assistance from the U.S. Army Engineer District, Mobile, and the Joint Airborne LIDAR Bathymetry Technical Center of Expertise (JALBTCX). The contributions made by the Mobile District and the JALBTCX to the workshop were invaluable due to their experience in the National RSM demonstration program. The workshop objectives were to 1) define what data are needed; 2) determine how to gather, manage, and present the data; and 3) prioritize current and emerging technologies based on needs. Invitations were sent out to the Districts, Divisions, U.S. Army Engineer Research and Development Center (ERDC) laboratories, other Federal agencies, and academia. Thirty-five participants attended the workshop. ERDC laboratories were represented by 13 attendees (Coastal and Hydraulics Laboratory, Information Technology Laboratory, Environmental Laboratory, Cold Regions Research and Engineering Laboratory), Corps Districts were represented by 13 (Mobile, Wilmington, Omaha, Detroit, New York, New Orleans, Jacksonville), academia was represented by 7 (University of Mississippi, University of Minnesota, University of Florida, Penn State University, Washington State University), and the Federal Interagency Sediment Program was represented by 2.

WORKSHOP

The 2-day workshop covered both the Local and Large-Scale Measuring and Monitoring Sediment Process research efforts. The following major topics were discussed:

- Regional Sediment Management Concepts and the Need to Define Information Requirements (William McAnally, Coastal and Hydraulics Laboratory)
- Data Acquisition Technologies at Multiple Scales (Brian Tracy, Cold Regions Research and Engineering Laboratory; Jeff Lillycrop, JALBTCX; Thad Pratt, Coastal and Hydraulics Laboratory)
- Data Management and Visualization Needs and Methods - SHOAL Tool Box (Lynn Hardegree, Mobile District)
- Synthesizing Information to Support Management Decision Making - RSM Demonstration (Susan Rees, Mobile District)

Researchers from the academia presented some current and emerging research efforts in the field of measuring and monitoring sediment process. The following topics were presented:

- Future Directions for Remote Analysis of Beaches and Inlets (Dr. Andrew Kennedy, University of Florida)
- An Acoustic Measurement Technique for Obtaining High-Resolution Sediment Properties (Dr. Charles Holland, Penn State University)
- Source Fate Impact Methodology (Dr. Thanos Papanicolaou, Washington State University)

- Suspended-Sediment Surrogate Technologies (Dr. Daniel Wren, University of Mississippi)
- Laser Altimetry Assessment of Riverbank Erosion, Blue Earth River, MN (Dr. Satish Gupta and Mr. Dave Thoma, University of Minnesota)

Two breakout sessions were also conducted, one on large-scale measurements and the other on local-scale measurements. This technical note includes only the portion on local-scale measurement. The session on the large-scale measurements will be discussed in a separate technical note.

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During the general workshop session, an overview on the concepts of RSM was presented. Issues such as environmental, economic, and social sustainability; variability in spatial and temporal scales; definition of sediment regions; and political and funding reality were discussed. Current technologies such as the use of light detection and ranging (LIDAR), multibeam sonar, side-scanning sonar, and acoustic Doppler current profiler (ADCP) were also presented and discussed. Mr. Jeff Lillycrop from the JALBTCX presented an informative overview on the use of the Scanning Hydrographic Operational Airborne LIDAR Survey (SHOALS) system and its contribution to the National RSM Demonstration Program at Mobile District. The use of the SHOALS system to obtain bathymetric and topographic data at the meso-scale was a valuable asset to the Mobile District during their involvement in the National RSM Demonstration Program.

The local-scale breakout session focused on measuring and monitoring needs as defined under the context of RSM. As the breakout session progressed, it became apparent that the data needs identified were beyond the resources of the local-scale measuring and monitoring research effort. At the end of the breakout session, the participants narrowed the needs down to the following as a good starting point:

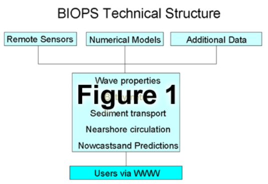
- Identifying sources and sinks at both temporal and spatial scales.
- Quantifying transport load.
    - Bed load.
    - Suspended load.

TECHNOLOGIES PRESENTED AT THE WORKSHOPS

The following is a summary of the technologies presented at the workshop. The presenters were invited to the workshop based on their past and current research efforts in the field of sedimentology.

Future Directions for Remote Analysis of Beaches and Inlets

The presenter was Dr. Andrew B. Kennedy from the University of Florida, Gainesville, FL. In his presentation Dr. Kennedy proposed the use of video techniques and X-band radars to monitor beaches and inlets remotely. He pointed out that information such as shoreline position; wave period, direction, and height; rudimentary underwater bathymetry; bar locations; general morphology; and shoreline beach slope can be obtained from shore-based video systems. The X-band marine radar can provide information on wave and current characteristics such as velocity, length, period, direction, and height. It can also provide bathymetry estimation over a wide area. Dr. Kennedy proposed creating a Web-based platform called Beach and Inlet Observation and Prediction Systems (BIOPS), where numerical modelers can access numerical models and real-time data from remote sensors to assist them in their research (Figure 1). The BIOPS platform proposed by Dr. Kennedy has some similarity to the Argus system in another RSM research effort titled "Argus-Based Morphologic Response Test Bed Database" proposed by Mr. William Curtis.



An Acoustic Measurement Technique for Obtaining High-Resolution Sediment Properties

The presenter was Dr. Charles Holland from Penn State University, Applied Research Laboratory (ARL), State College, PA. Dr. Holland has been conducting seabed characterization using acoustic techniques as part of the underwater mine detection program for the U.S. Navy for many years. In his presentation, he described a promising new technique for geoacoustic inversion that provides high-resolution, subbottom layering structure. The technique relies on reflection and scattering of acoustic energy to provide useful data for extracting physical properties and geometry of sedimentary strata (sediment density, porosity, sound speed, and attenuation). Dr. Holland indicated that silty clay is a common sediment type in shallow water that typically originates from terrestrial sources. The fine-grained sediment exhibits properties that play an important role in this new technique. One property of the silty clay is that the speed of sound through its bulk medium is lower than that of the seawater, and another property is that it has a density greater than seawater. The geoacoustic inversion technique applies a classical theory that predicts an angle at which the reflection coefficient is zero and a total transmission of sound into the seabed when the fine-grained sediment is at the water-sediment interface. This angle is known as the angle of intromission δ (Figure 2). The subscript in the angle of intromission equation refers to the layer number (i.e., water and seabed). The geoacoustic inversion technique relies on measuring the reflection coefficient versus angle. From these two measurements, the angle of intromission, δ, and the normal incidence pressure reflection coefficient, ν, can be easily extracted. With these two parameters along with the density, ρ_1, and velocity, c_1, of the seawater; the density, ρ_2, and velocity, c_2, of the sediment can be obtained from the following equation

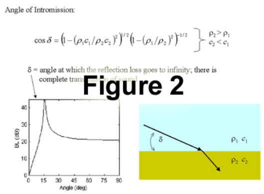


Figure 2

$$\rho_2 = \rho_1 \{1 - 4\nu / [\cos \delta(1 + \nu)]^2\}^{-1/2}$$

$$c_2 = \rho_1 c_1 / \rho_2 (1 + \nu) / (1 - \nu)$$

This geoacoustic inversion technique is quite elaborate, and the deployment/measurement scheme is illustrated in Figure 3. Dr. Holland has tested the technique at 20 sites in the Mediterranean, 8 sites off the New Jersey shelf, and 4 on the Scotian shelf. At this time, the technique is applicable only to fine-grained sediment such as silty clay.

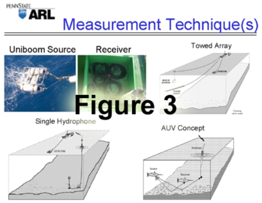


Figure 3

Suspended-Sediment Surrogate Technologies

The presenter was Dr. Daniel Wren from the University of Mississippi, Oxford, MS. Dr. Wren's current research includes the measurement of suspended sediments using acoustic backscattering. Dr. Wren gave an overview of current technologies and how they are used as a surrogate in the measurement of sediment transport. Some of the technologies touched on by Dr. Wren included optical, nuclear, remote spectral, laser, digital optical, acoustic backscatter, vibrating tube, impact, and differential pressure. The purpose of Dr. Wren's presentation was to provide a better understanding of current technologies as a surrogate tool.

Laser Altimetry Assessment of Riverbank Erosion, Blue Earth River, MN

The presenters were Dr. Satish Gupta and Mr. Dave Thoma from the Department of Soil, Water, and Climate, University of Minnesota in St. Paul, MN. Dr. Satish and Mr. Thoma gave an overview of a riverbank erosion study they conducted using LIDAR along the Blue Earth River in Minnesota. The technique and equipment used in this study were similar to the SHOALS system used by the JALBTCX (Figures 4 and 5). The SHOALS system contains both a topographic laser and a hydrographic laser, while the commercial system used by the University of Minnesota contains only a topographic laser. The SHOALS system is currently a more advanced system, and an upgrade is in the works to expand its capabilities further. During the workshop, the two groups had a chance to exchange ideas and plan possible future collaboration.

Figure 4

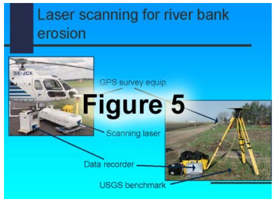


Figure 5

PROMISING NEW TECHNOLOGIES

The following technologies seem to best address the needs identified at the Mobile workshop: Integrated Surface Difference over Time, Particle Velocimeter and Flux Meter, Source Fate Impact Methodology, and Noncontact Radar. Some of the technologies were identified during the workshop, while others were identified afterwards in follow-up discussions.

Integrated Surface Difference over Time Technique (ISDOT)

The ISDOT technique (Abraham and Pratt 2002) was not presented at the workshop, but does have potential applicability. Mr. David Abraham of the Coastal and Hydraulics Laboratory, Vicksburg, MS, ERDC, is currently working on the ISDOT technique as part of the Monitoring of Completed Navigation Projects (MCNP) to determine the bed-load transport rate in large sand-bed rivers. The ISDOT technique uses multibeam sonar bathymetric data to quantify a bed-load transport rate for a given river cross section. The ISDOT technique has been applied to actual bathymetric data sets taken at Pool 8 (Figure 6) on the upper Mississippi River, just south of La Crosse, WI. When compared to some of the standard bed-load estimation methods such as Einstein's, Toffaleti's, and van Rijn's functions, the initial results were surprisingly close and look very encouraging. The ability to quantify bed-load transport rate in a meaningful manner will have a significant impact in the RSM Program.

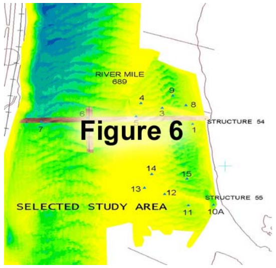
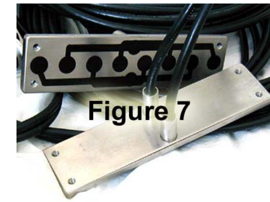
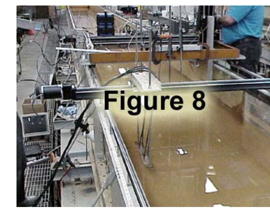


Figure 6

The test at Pool 8 (Abraham and Pratt 2002) involved taking four swaths (at least two are required for the ISDOT technique) of bathymetric data across the width of the river at different times for the same spatial location. The coordinates of a spatial location common to the four acquired swaths of bathymetric data were identified from the Global Positioning System (GPS). Using the identified common coordinates as a reference point, computational spatial grids consisting of a 1-ft square were made for the width of the river. The four data sets were then superimposed over these computational spatial grids, generating four sets of bathymetric data that represent the exact spatial location on the river at four different points in time. The change in volume of a computational grid between any two given times can be determined by calculating the volume between the surface of the computational grid at time t_1 and the same computational grid surface at time t_2. By applying the same time frame to all the computational grids on the same row for the width of the river, the net change in volume for a row can be determined by summing the volume change of each computational grid. The net change in volume for a row can then be multiplied by the density of the sediment-water mixture for that row to yield a bed-load transport rate. Presently, both deposition into and scour out of any element are considered as positive transport.

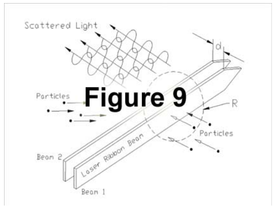
To assist in validating the ISDOT technique and determining its accuracy in estimating bed-load transport rate, a series of flume tests was conducted at the Agricultural Research Services National Sedimentation Laboratory in Oxford, MS, during December, January, and February of FY03. To obtain the profile of the test flume sand bed, an acoustic sand bed profiler measurement system was purchased from Seatek Instrumentation and Engineering, Alachua, FL. The Seatek acoustic sand bed profiler measurement system consisted of two stainless steel racks housing eight acoustic sensors spaced 25 mm (1 in.) center-to-center (Figure 7) and a thirty-two-channel data acquisition system with software. The sensor racks were mounted parallel to the length of the flume on an automatic traversing mechanism spanning the width of the flume (Figure 8). The automatic traversing mechanism moved the sensor rack back and forth across the width of the flume at one location to record the profiles of the sand bed as it passed underneath. The data acquisition system recorded the outputs from the sixteen acoustic sensors and the position encoder of the traversing mechanism. A Dynatrol density meter was also mounted at the end of the flume on the return pipe to measure the total transported sediment. A surface profile of the flume sand bed will be generated from the outputs of the acoustic sensors and the position encoder of the traversing mechanism. The data will be used in the ISDOT method to calculate the bed-load transport rate, and the results will be compared to the results of the Dynatrol density meter. The RSM Research Program is funding the instrumentation portion of the test. A complete report documenting the flume tests and results will be generated in FY04.

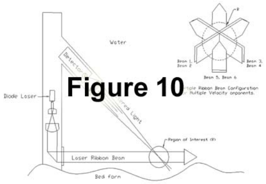




Particle Velocimeter and Flux Meter

Dr. Jan Northby of the Department of Physics at the University of Rhode Island, Kingston, RI, has developed a particle velocimeter and flux meter using a new optical technique (Northby 2002). The technique uses noncoherent light to measure current velocity, suspended sediment particle size, and suspended particle size distribution at the water-sediment interface. Dr. Northby has built a prototype device and has conducted some very limited flume tests in ocean water with the device. Initial data indicated that the technique works. Currently in its simplest form, the technique uses two diode lasers to project two parallel, noncoherent ribbon beams at a distance *d* apart into a targeted area (Figure 9). As the suspended sediments cross the two beams, the lights from the beams are scattered. A photo-multiplier tube (PMT) detector (Figure 10) detects the scattered light and outputs the signals to a data acquisition system to produce two pulses. By calculating the time difference or delay between the two pulses, a velocity component can be determined. The particle size can be determined from the intensity or height of the pulse. From theory, it is reasonable to presume that the amount of light scattered is proportional to the size of the particle. The bigger the particle, the more light it scatters, which translates into a bigger pulse height. From the pulse height distribution, one can also determine the particle size distribution for a given volume. Velocity components for multiple axes can be obtained by using multiple ribbon beam pairs orientated orthogonal to each other (Figure 10). The scattered light from each beam can be identified and tagged by turning the beams on and off (modulating) at a different frequency. Another method that reduces the number of frequencies is to lock in each beam at a different phase angle. For example,





locking in beam one at Φ=0 and beam two at $\Phi=\Pi/2$ can reduce the number of frequencies used from two to one.

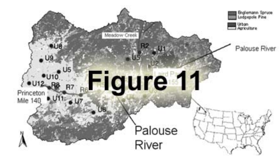
The device was demonstrated in a circular water tank filled with sand-filtered seawater at the University of Rhode Island. The initial demonstration was very limited in scope due to funding, but the results were very promising. During the water tank test, the device was able to detect current velocity up to 15 cm/sec, particle size greater than ~30→35μm, and 16.3 partials/cm^3 for a swept volume of 9.47 cm^3. Dr. Northby pointed out that this was a proof-of-concept prototype. He is working on developing a more compact and robust version of the device. He is also working on developing a more comprehensive test program for the device to determine its practical limitations and capabilities. When some of the laser/detector set-up parameters are changed, the device can be fine-tuned to meet certain sampling conditions and requirements. For example, the width of the laser ribbon can be varied to look at different sampling volumes, the placement of the laser and detector can be varied to optimize detection due to different sediment concentrations, and the distance between the ribbon beam pair can be varied to optimize for particle size and current velocity.

Being optical, this device faces the same problem that plagues all optical devices such as fouling of the optical window. One advantage this device has that most other optical devices do not have is that it uses noncoherent rather than coherent laser. By creating a ribbon beam at the source and using a cone pattern at the detector, it is less sensitive to fouling interference as opposed to using a point source like most other optical devices.

The ability to measure current velocity, particle size, and particle size distribution at the water-sediment interface is a very important need in the RSM Research Program. This device has demonstrated that it is capable of measuring these parameters. The question is "How well can the device perform under actual field conditions?"

Source Fate Impact Methodology, the Use of Natural Stable Isotopes To Identify Sediment Source

Dr. Thanos N. Papanicolaou, Department of Civil and Environmental Engineering, Washington State University, Albrook Hydraulics Lab, Pullman, WA, is currently working on a technique to use natural, stable isotope to identify the source of in-stream fine sediment (Papanicolaou et al. 2002). The technique involves using naturally occurring stable carbon and nitrogen isotope compositions coupled with measurements of carbon/nitrogen (C/N) ratios. This technique has been used successfully to identify sources of sediment organic matter in rivers (Onstad et al. 2000) and to differentiate between terrestrial and marine sources of organic matter in estuary sediments (e.g., Middelburg and Nieuwenhuize 1998). Dr. Papanicolaou has applied this technique in a study funded by the National Oceanic and Atmospheric Administration Sea Grant Office in the Palouse Watershed in eastern Washington to identify the sources of upland sediment. With thorough consideration and analysis of the factors that control and modify the C/N ratios and C and N isotopic compositions of soils and in-stream sediments, he was able to discriminate between agricultural (mainly wheat) and forest soils.



For the study, Dr. Papanicolaou collected 50 samples from the upland stations (labeled U stations in Figure 11) on the Palouse River. The samples were analyzed using a Finnigan MAT Delta Plus mass spectrometer from the University of Idaho. Approximately half of each sample was used to determine the C and N content and isotope composition in the total sediment matter while the other half was used to determine the C and N content and isotope composition in the organic matter.

Preliminary results indicated a distinct signature between agricultural and forest soils in terms of the C/N ratio, $\delta^{13}C$, and $\delta^{15}N$. The C/N ratio for forest soil was 17.05 versus 11.62 for agricultural. The $\delta^{15}N$ for forest soil was 0.8 versus 5.6 for agricultural, and the $\delta^{13}C$ for forest soil was –28.7 versus –26.7 for agricultural. Dr. Papanicolaou pointed out in his study that the $\delta^{13}C$ of the agricultural soil appears to reflect the isotopic composition of C4 vegetations (corn, barley, lentil, and pea) that were grown in the region, whereas the forest has an isotopic composition indicative of predominantly C3 vegetations (tree, shrub, and grass). As a result of this monoculture environment, it is expected that the agricultural soil has a smaller isotopic variability than the forest soil.

Like all scientific techniques, there are limitations and factors that influence the results. In order to use the stable isotope technique, the following two conditions must be met: (1) variation between sources must be greater than the variation within, and (2) any modification of the fingerprint due to upland and in-stream biogenic processing must be accounted (Papanicolaou et al. 2002). Some factors and environmental conditions that can influence or modify the isotope ratio and composition are drought (both soil and atmospheric), elevation, and fertilization. Careful considerations must be given to these factors and conditions when utilizing the stable isotope technique.

Dr. Papanicolaou is looking to refine and further establish this technique by applying it to other regions and placing emphasis on the analyses of the factors (e.g., climatic conditions, latitude) that control and modify the isotopic composition of sediment. The stable isotope technique has the potential to be a powerful tool for sediment fingerprinting that can help in the determination of sediment sources and sinks.

Noncontact Radar

The use of pulsed Doppler radar to measure water surface velocity and ground-penetrating radar (GPR) to measure river depth profiles has existed for a number of years. The idea of using the two in combination mounted on a helicopter to compute river discharge is relatively new. Research scientists at the Applied Physics Laboratory of the University of Washington (APL/UW) and at the United States Geological Survey (USGS) conducted a series of joint studies using both the pulsed Doppler radar and GPR to measure river surface velocity and river bottom profile to calculate river discharge (Melcher et al., in press). The studies were conducted between September 2000 and May 2001 on the Lewis, Toutle, and Cowlitz Rivers located at the southwestern part of Washington State, close to the Columbia River. At the end of the study, it was concluded that a large number of discharge measurements can be computed rapidly from the data obtained from the helicopter-mounted radar measurements and within reasonable accuracy of conventional methods.

The measurement system used in the study consisted of a pulsed Doppler radar, a GPR, differential global positioning system (DGPS), and an attitude and heading reference system (AHRS). The pulsed Doppler radar was developed at APL/UW and mounted underneath the helicopter with one antenna pointed directly toward the front and the other directly to the rear. The Doppler system transmits 10-GHz pulses for 50 ηsec every 25 μsec and receives the backscattered power in 64-range bins that are spaced 7.5 m apart. The purpose of using the range-gated system was to investigate the maximum distance from the helicopter that the signals could be detected. The Doppler radar measures surface velocity by measuring the Doppler shift in the signals scattered back from a rough water surface based on the Bragg scattering and composite surface theory. In this application, the helicopter downwash enhances the water surface waves, and the technique used by APL/UW was able to separate the intrinsic phase speed of the waves including those generated by the helicopter downwash from the naturally occurring waves of the surface current. The phase speeds of the Bragg waves generated by the helicopter downwash always produce negative Doppler shifts because the waves are moving radially away from the helicopter. At the same time, the downstream waves of the river also produce negative Doppler shifts because they are moving away from the helicopter, while the upstream waves produce positive Doppler shifts because they are moving toward the helicopter. By subtracting the Doppler shifts produced by the waves on the upstream side from those produced on the downstream side the helicopter, a result can be obtained that is directly proportional to the surface velocity, assuming the Doppler radar antennas are aligned to look directly upstream and downstream (Melcher et al., in press).

A commercially available GPR was mounted underneath the helicopter to measure river depth. The GPR transmits an electromagnetic wave at 100 MHz that penetrates both air and water. The GPR measures the time of reflection to each medium. Reflections occur wherever there is a change in the dielectric constant of the medium through which the electromagnetic wave travels. Since the electromagnetic wave at 100 MHz travels nine times slower in water than in air, the river depth can be determined based on the time difference between the river surface and bottom reflections.

In order to determine the position of the helicopter across the width of the river, a DGPS was mounted in the helicopter cockpit. The effects of the helicopter pitch, roll, and yaw greatly influence the accuracy of the Doppler radar in obtaining surface current. To remove these effects from the Doppler shift, an AHRS was mounted in the tail of the helicopter.

APL/UW is currently developing a smaller version of the 10-GHz pulsed Doppler radar that can be mounted on a fixed structure to measure current velocity. A commercial version will be available within the next 2 years.

CONCLUSION

The technologies covered in this technical note are just a few examples of those that are current and emerging. Based on the needs defined at the Mobile workshop and limitation of funding, the following technologies were identified for further investigation:

- Integrated Surface Difference over Time Technique (ISDOT).
- Particle velocimeter and flux meter.
- Source fate impact methodology and natural stable isotopes to identify sediment source.

The ISDOT and the particle velocimeter and flux meter can play an important role in measuring and monitoring suspended sediment and bed-load transport, while the natural stable isotopes technique can play an important role in the identification of sources and sinks. The first two technologies have some additional advantages in that they have been through the proof-of-concept stage and are leveraged by other programs. The third technology requires a 1- to 2-year study period and is limited in application. Some of the other technologies covered in this technical note are already covered by other research efforts within the RSM Research Program (such as Mr. William Curtis' research effort "Future Directions for Remote Analysis of Beaches and Inlets") or by other research programs within the Corps (such as "Laser Altimetry Assessment of Riverbank Erosion, Blue Earth River, MN," which is covered by the SHOALS system). The noncontact radar technology is part of a program called Hydro21 created by the USGS in concert with APL/UW to investigate noncontact measurement technologies. USGS is interested in sharing its Hydro21 technologies with other Federal agencies. The author had a meeting with Dr. William J. Plant, Principal Research Scientist, of APL/UW in Seattle in September 2002 to discuss the noncontact radar. The meeting was very fruitful, and Dr. Plant provided some points of contact at USGS for future collaboration

KEYWORDS: Spatial, Temporal, Bathymetry, LIDAR, Topographic, Meso-scale, Morphology, Geoacoustic, Terrestrial, Intromission, Multibeam, Bed load, Velocimeter, Flux meter, Noncoherent, Isotope, Noncontact radar, Doppler radar, Ground-penetrating radar

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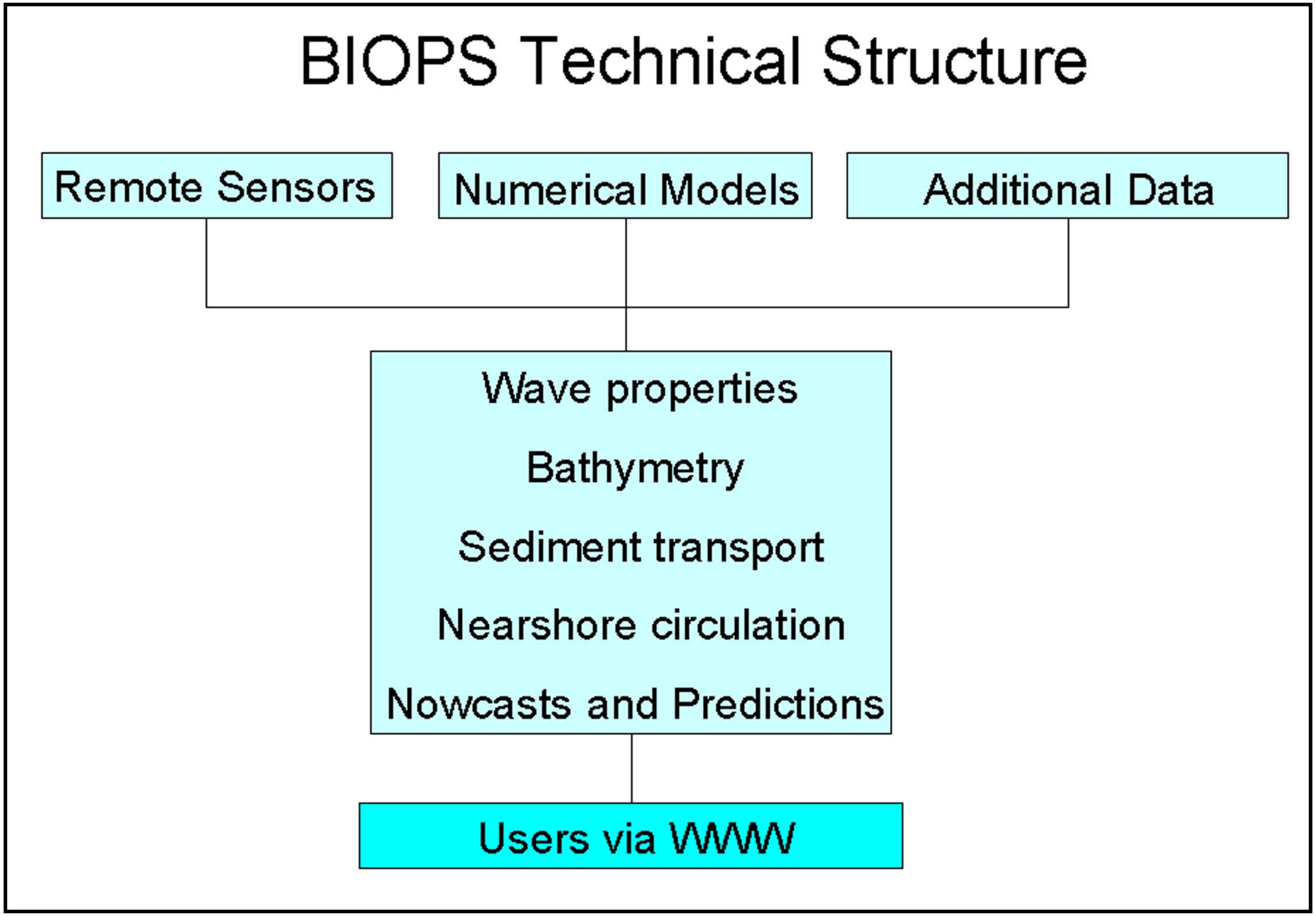

Figure 1. Web-based BIOPS platform

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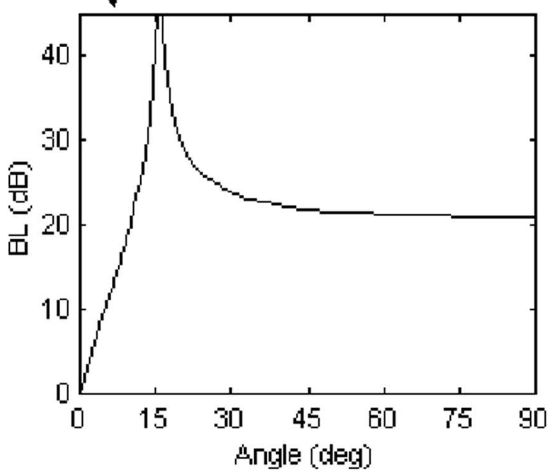
Angle of Intromission:

$$\cos\delta = \left(1-\left(\rho_1 c_1/\rho_2 c_2\right)^2\right)^{1/2}\left(1-\left(\rho_1/\rho_2\right)^2\right)^{-1/2} \quad \left.\right\} \begin{matrix} \rho_2 > \rho_1 \\ c_2 < c_1 \end{matrix}$$

δ = angle at which the reflection loss goes to infinity; there is complete transmission of sound



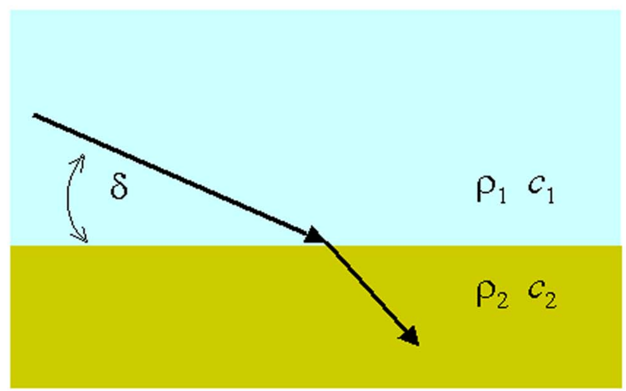


Figure 2. Equation for angle of intromission

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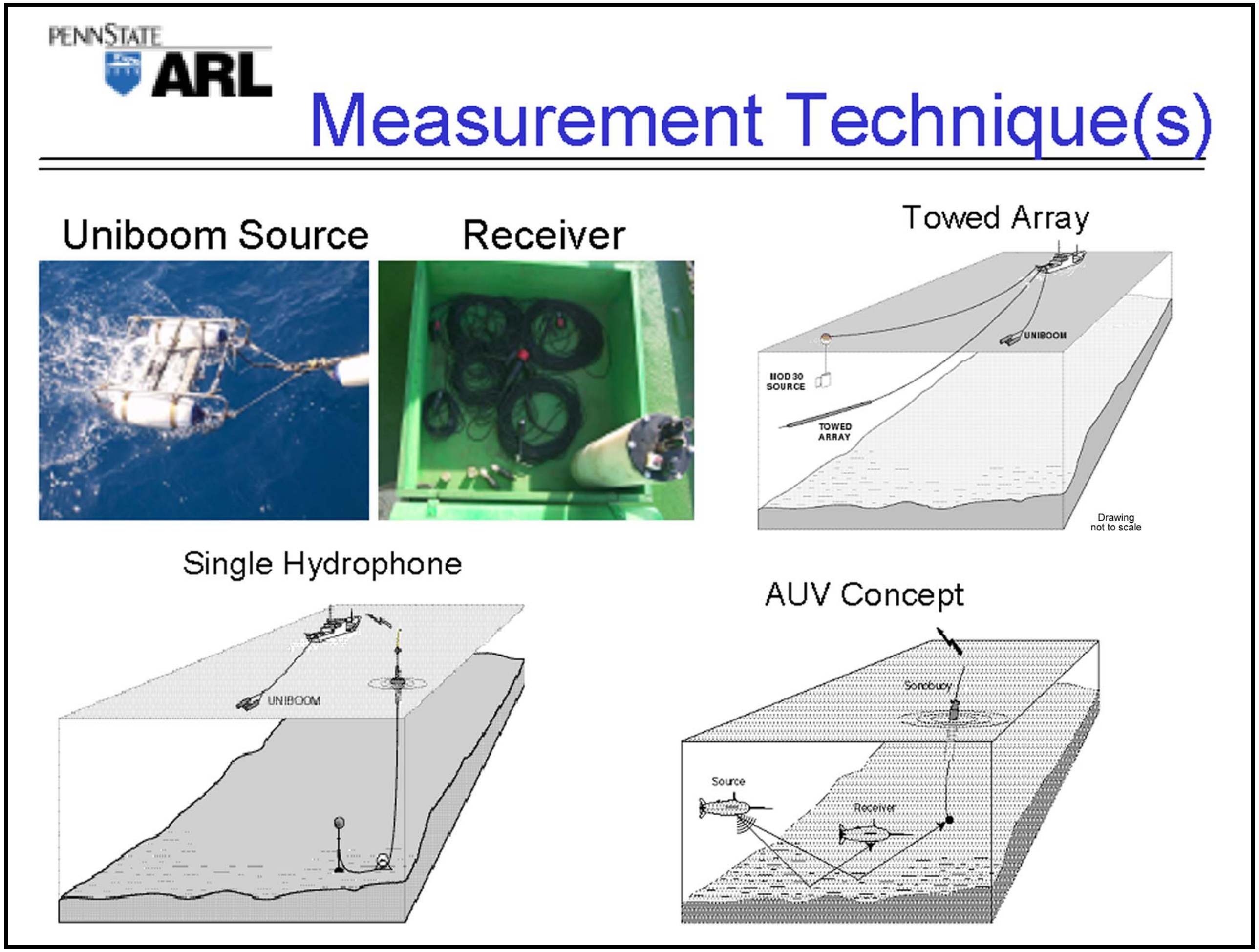

Figure 3. Penn State University, Applied Research Laboratory (ARL) deployment/measurement scheme (Note: AUV = Autonomous Unmanned Vehicle)

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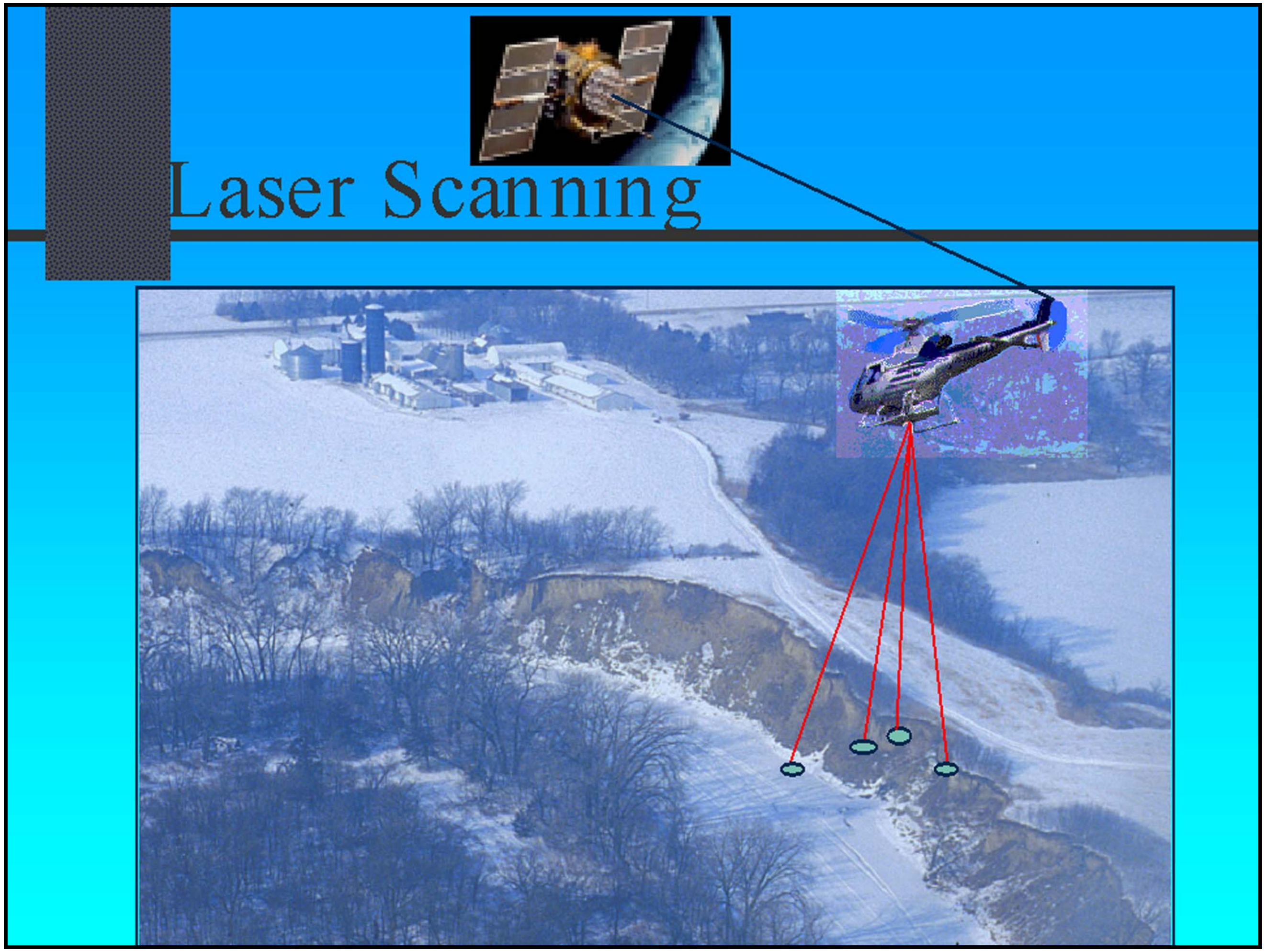

Figure 4. LIDAR scanning technique

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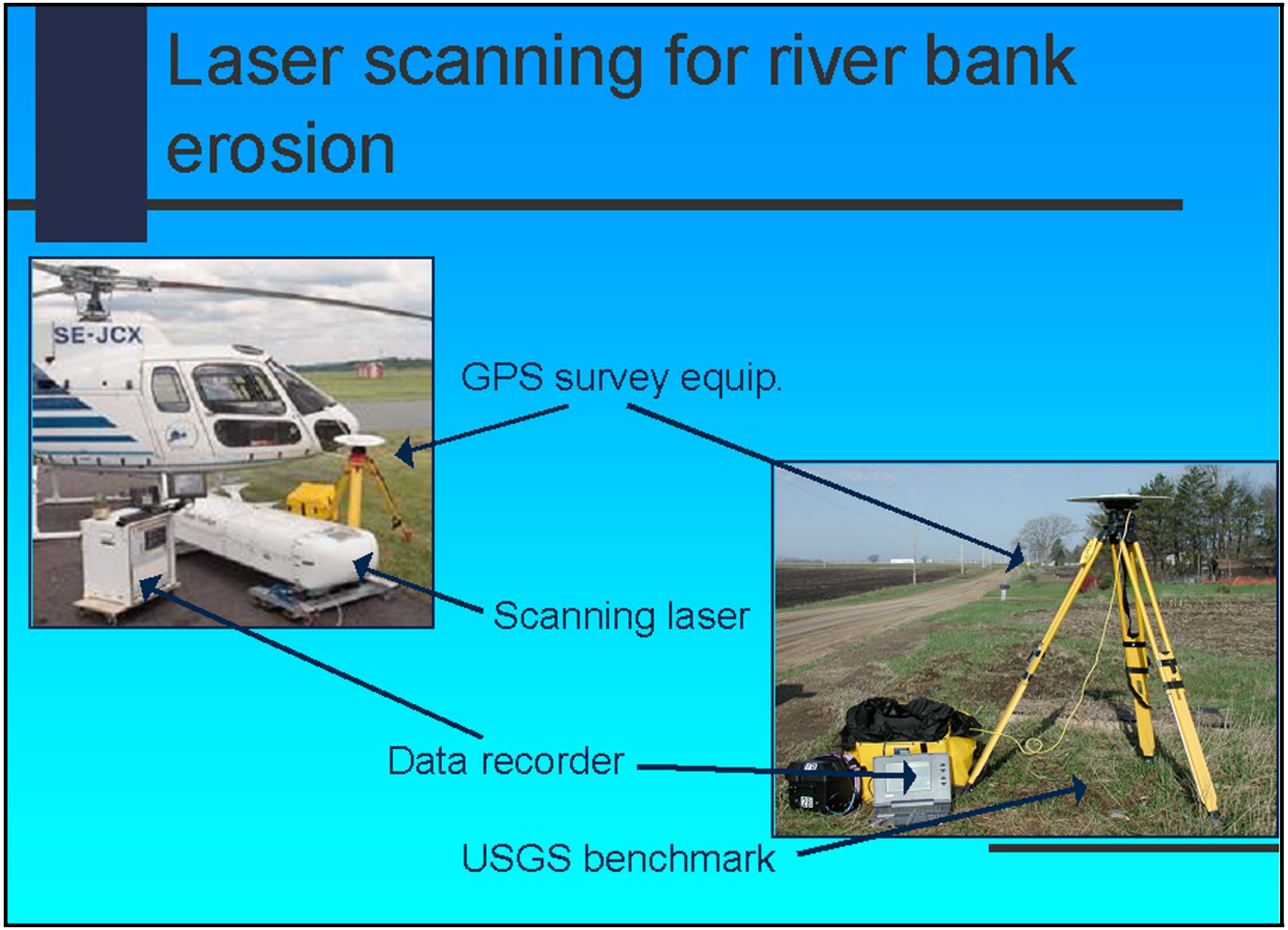

Figure 5. LIDAR system

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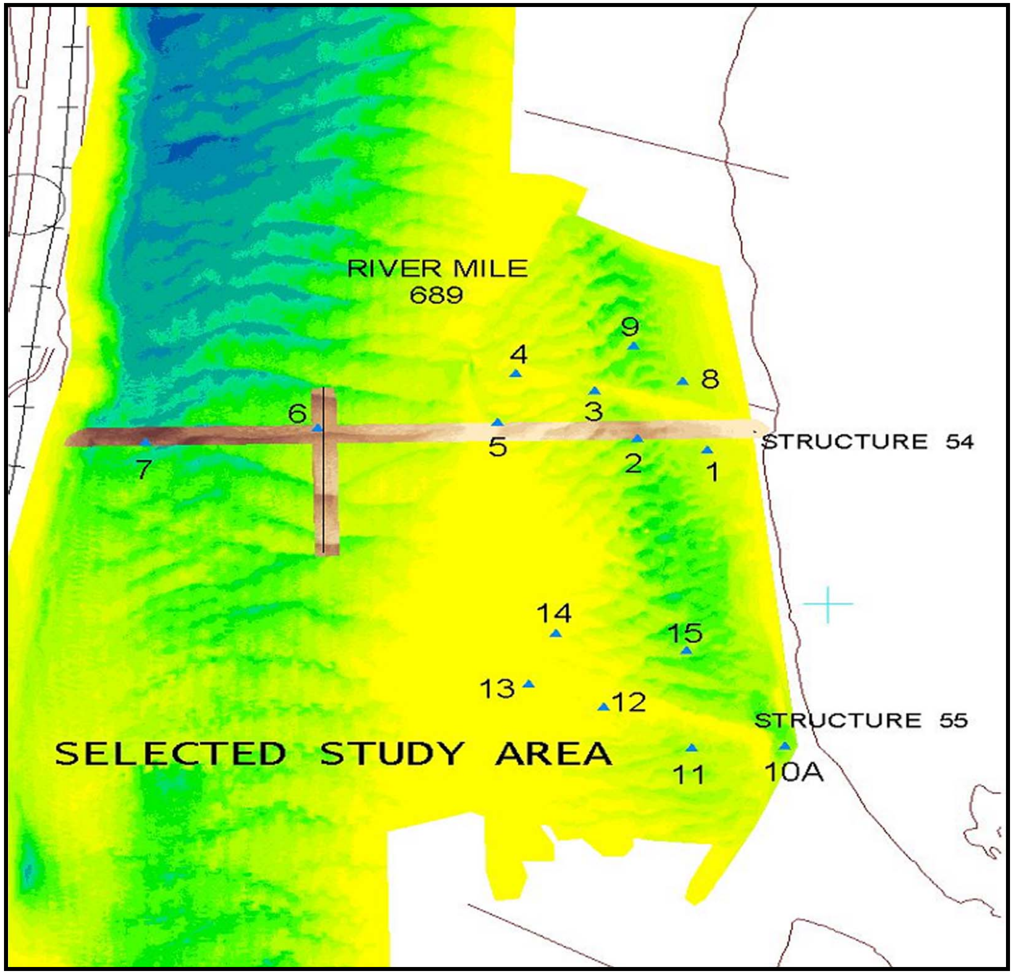

Figure 6. Small section of bathymetric data taken at Pool 8. The brown areas represent special timed lateral and longitudinal swaths

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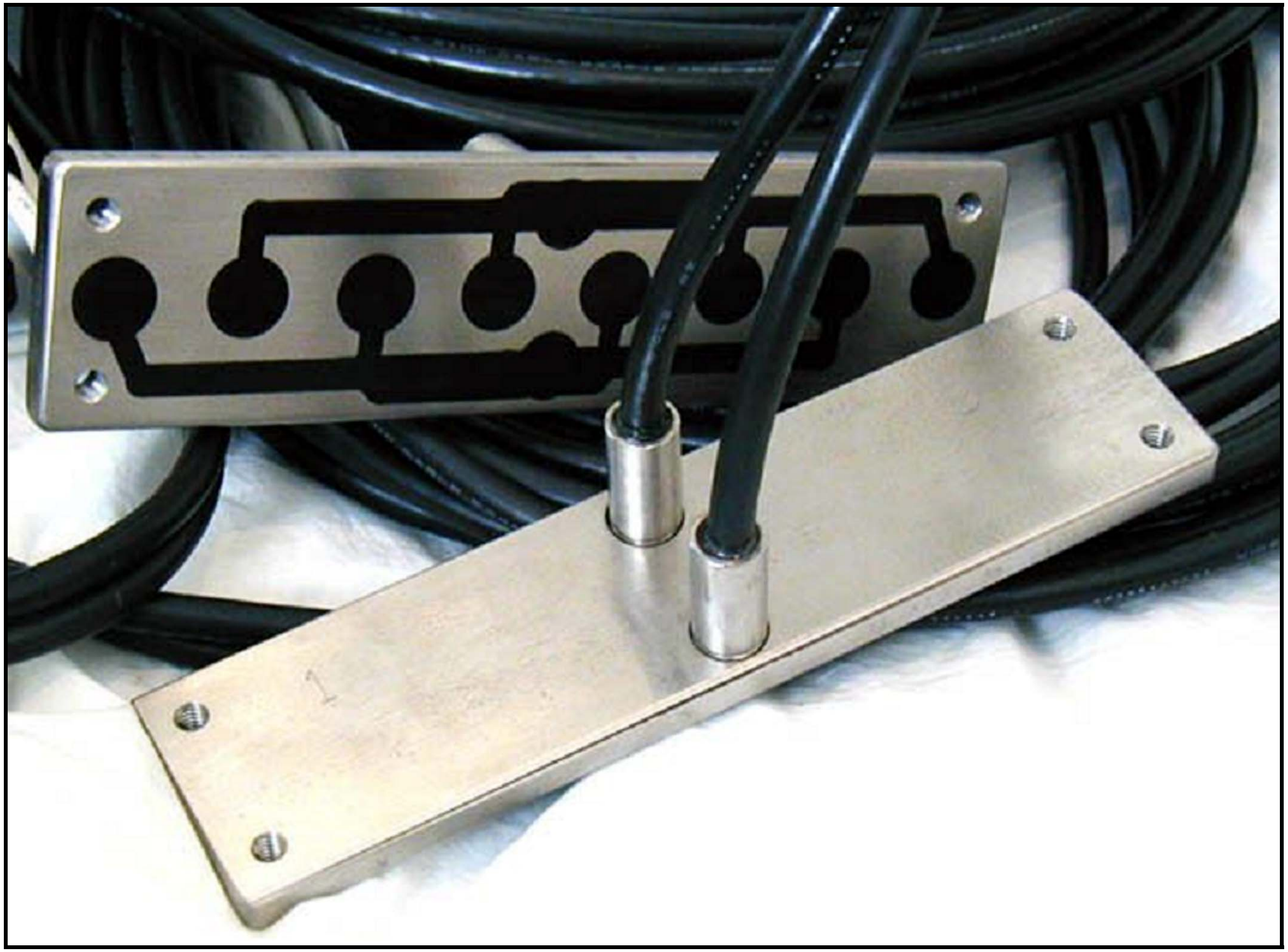

Figure 7. Seatek stainless steel sensor rack

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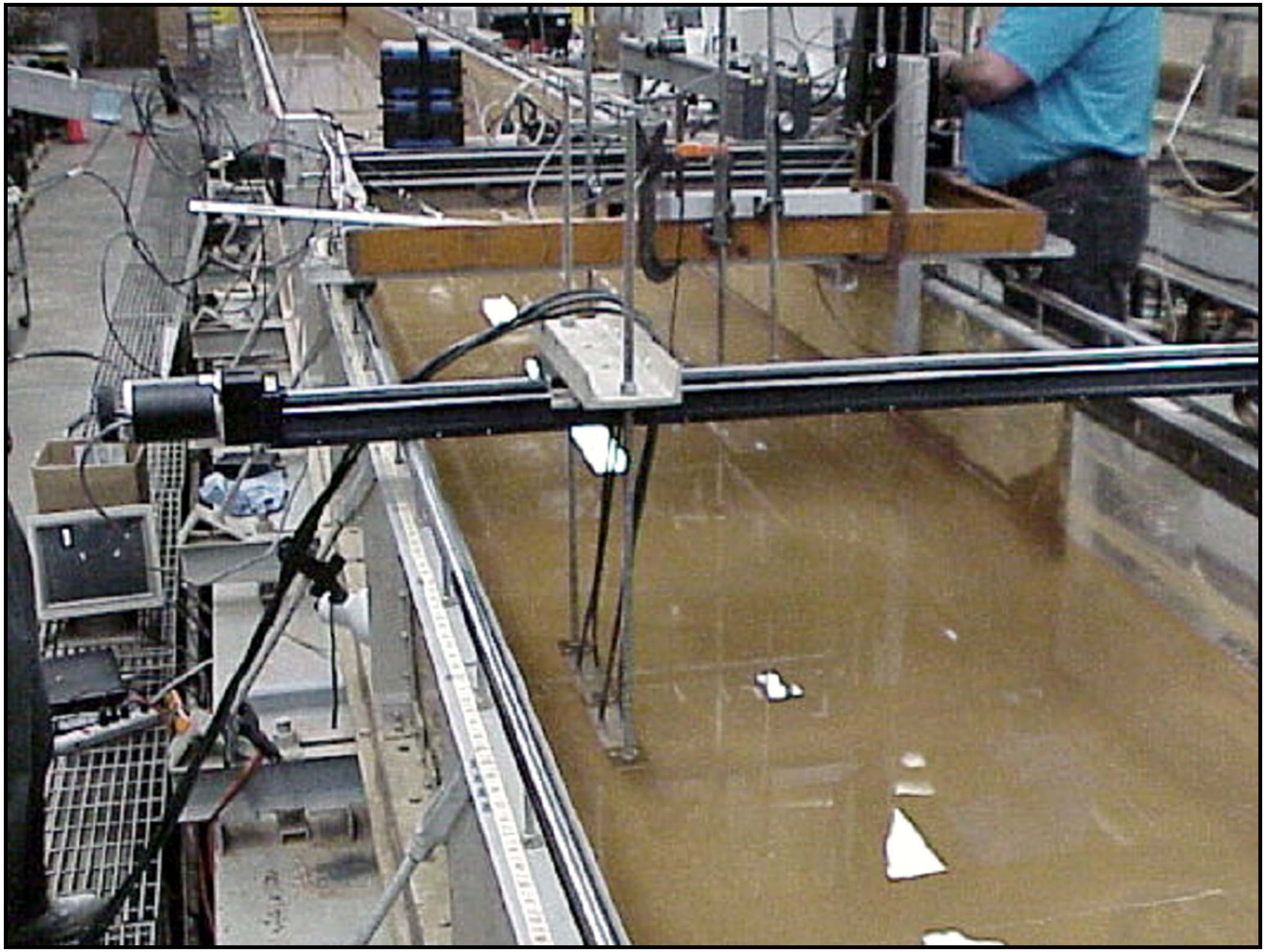

Figure 8. Seatek acoustic sensors mounted on the automatic traversing mechanism in test flume

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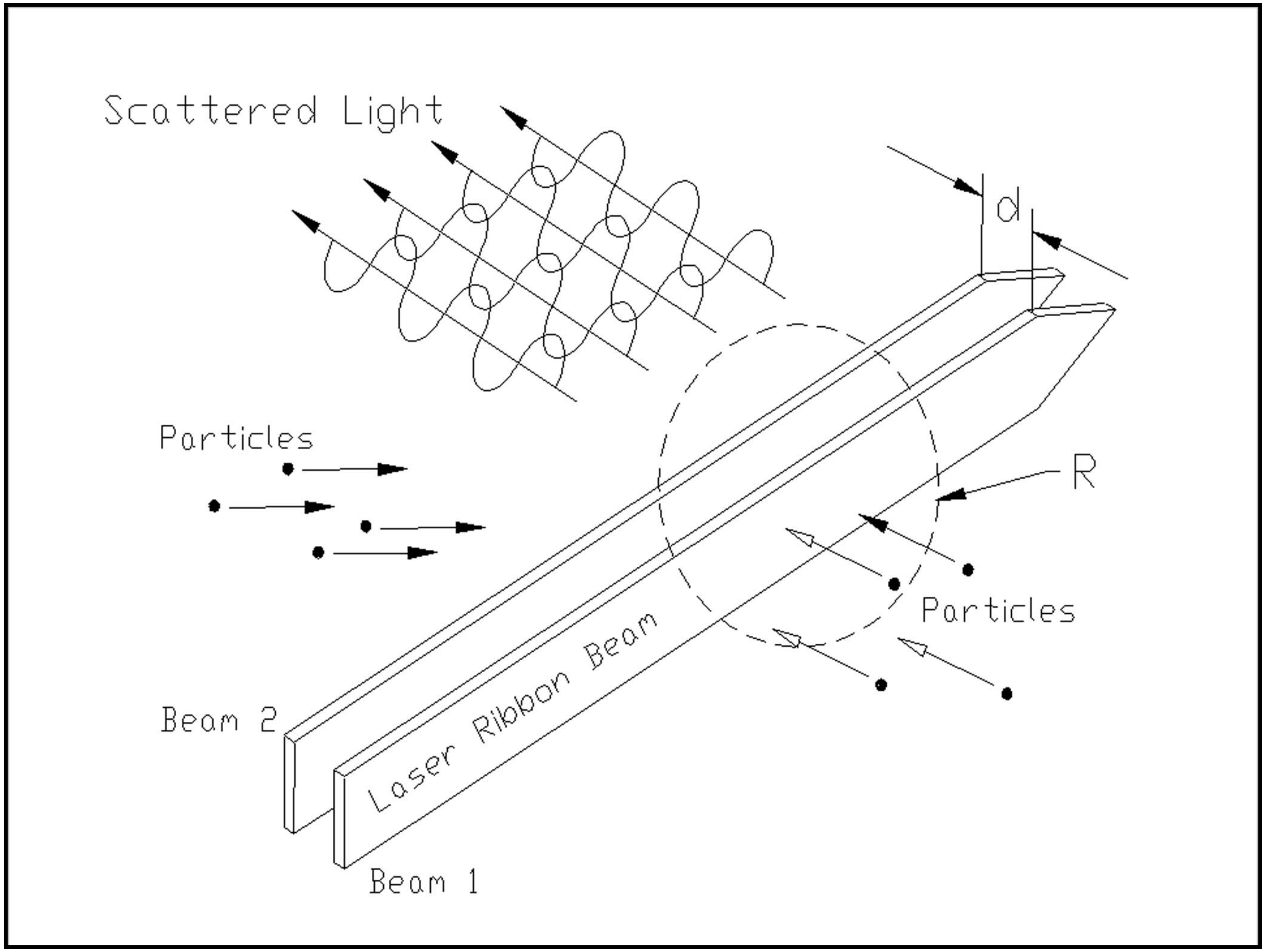

Figure 9. Simplified diagram of the two-beam technique

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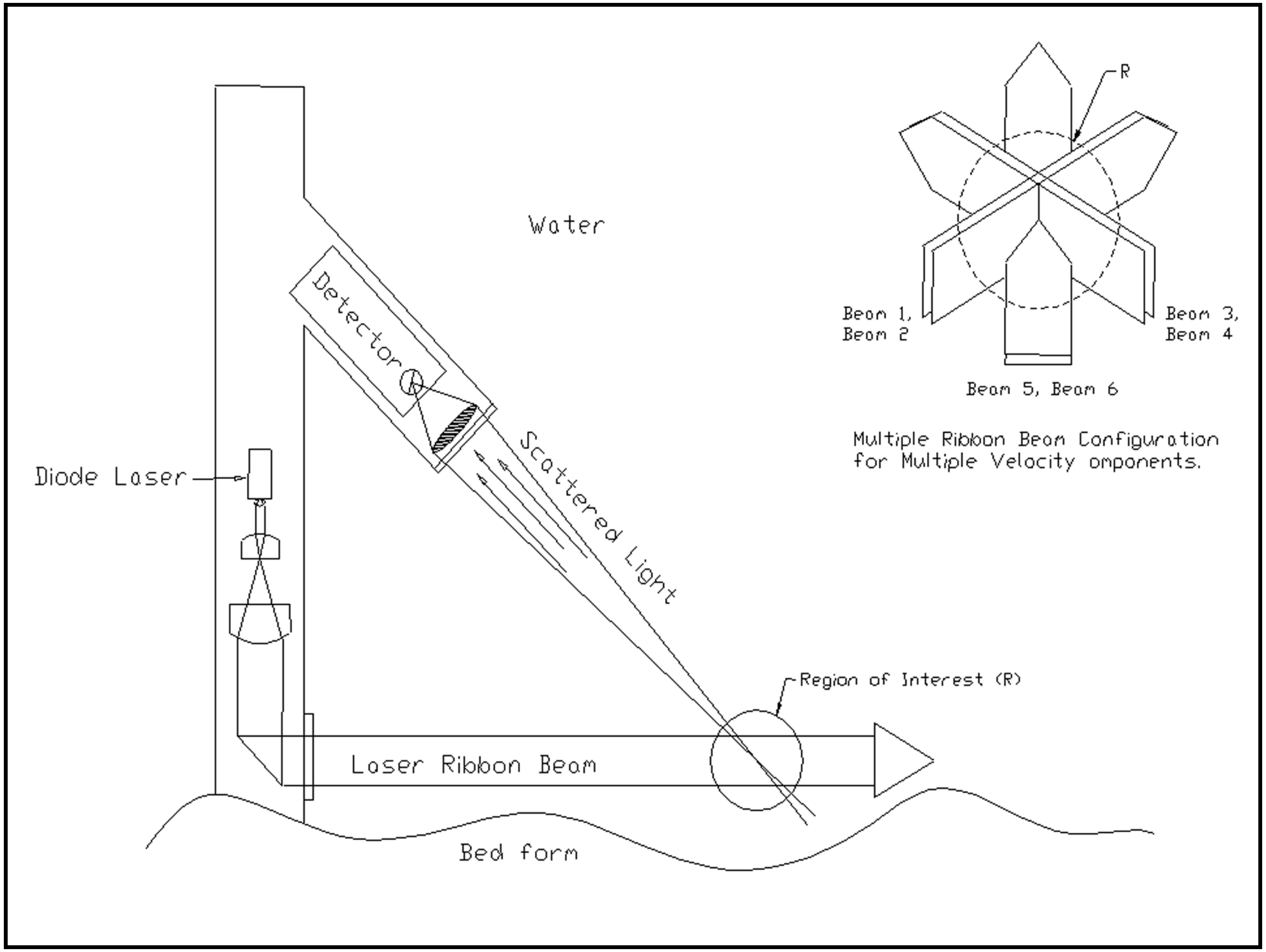

Figure 10. Laser and detector configuration and multiple ribbon beam configuration

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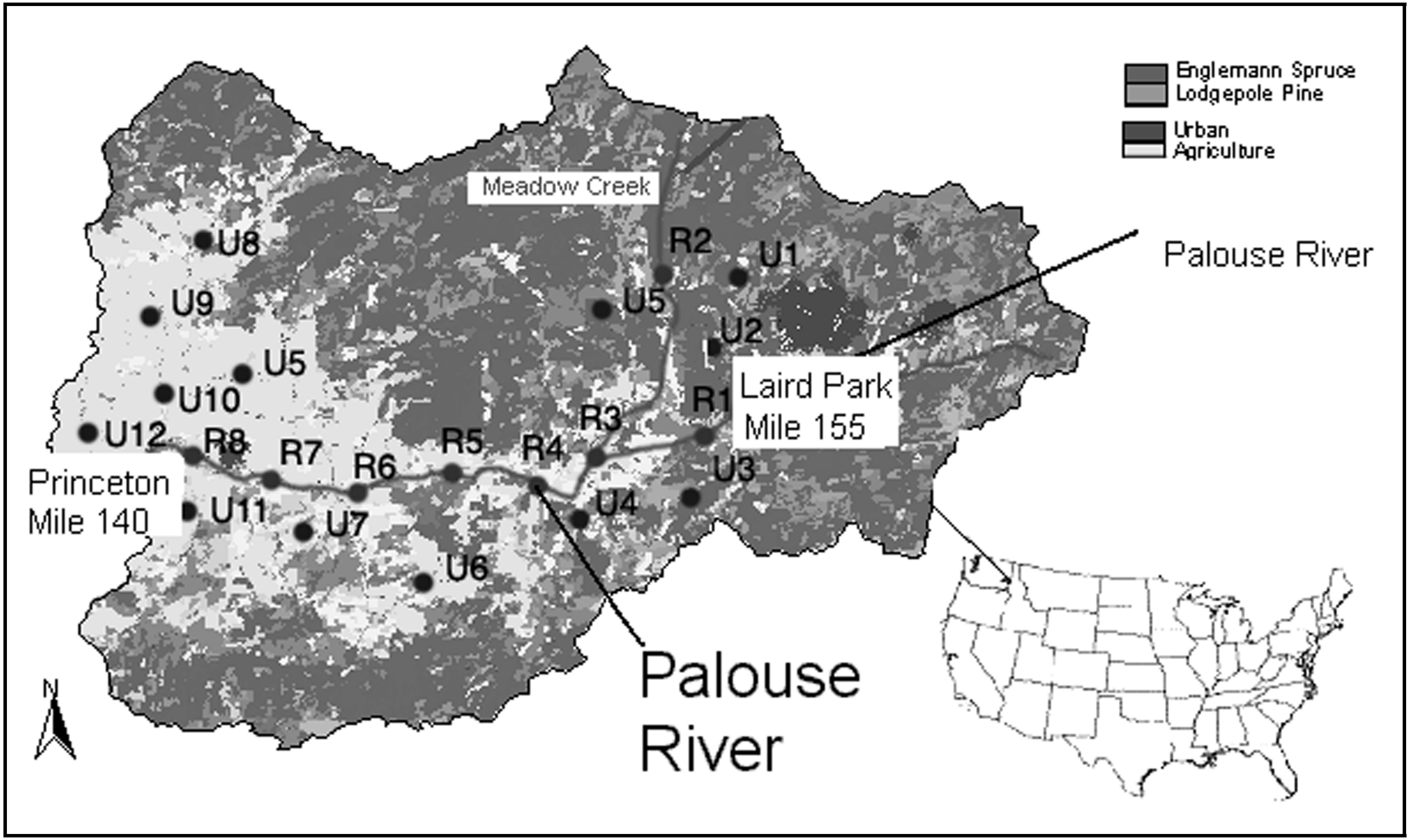

Figure 11. Map of the Palouse Watershed study area with upland (U) and river (R) sampling locations

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