SPATIAL ANALYSIS OF ADCP DATA IN STREAMS

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ABSTRACT

Procedures to display data from acoustic Doppler current profilers (ADCPs) in spatial maps have been developed for surface-water hydrology. The procedures were designed for rapid processing of repeated ADCP surveys of channel reaches and junctions. Using only ADCP data, vectors that define the velocity field of a channel can be displayed in perspective over detailed bathymetry. In addition, the backscatter intensity recorded with ADCP velocity data provides a sediment-transport indicator. The prevalence of ADCPs and their ability to measure velocity fields encourages the exploitation of backscatter-intensity values for sediment-transport studies. At present, spatial ADCP data from channel surveys have been interpolated to volumetric vector grids to show flow and sediment dynamics through time animation. These visualizations have highlighted some discrepancies between expected flow properties and analyses of ADCP data, and field experiments are suggested to identify their origin. Examples are given in this paper using spatial ADCP data collected in the Sacramento and San Joaquin Rivers, California, during 2001 and 2002.

INTRODUCTION

The water-quality data files of the U.S. Geological Survey (USGS) contain instantaneous sediment concentrations measured by sampling water at multiple points across streams. Hydrologists recognize that concentrations represent brief samples of a constituent that fluctuates with turbulence and changing discharge. To compensate for this uncertainty, we use statistical adjustments and smoothing techniques to approximate an average concentration for a given period. Standard analyses can produce crude sediment-discharge totals from these values, but water sampling does not resolve fluctuations in sediment transport that are exhibited at macroturbulent scales (tens of seconds, usually). Sediment suspension also varies spatially in relation to local sediment sources and hydrodynamics. Turbulent fluctuations and spatial variations both increase the uncertainty in sediment-transport quantities, and a record of the fluctuations and their location will at least identify, and perhaps reduce, the uncertainty inherent with sediment sampling.

Spatial-analysis procedures have been developed for data collected with the ADCPs that are presently used by the USGS for discharge measurements. ADCPs have the potential to provide data on sediment suspension at numerous points in the vertical column, for time intervals on the order of 1 second. An ADCP transmits sonar signals and calculates velocity from the Doppler shift in the frequency of the signals returned from multiple depths beneath the device. From the same depths, the ADCP software records backscatter intensity, which is the intensity of acoustic backscatter from solid particles suspended in the flow. By recording ADCP data when crossing a stream, we acquire sediment-transport indicators over the flow depth every 1 to 4 seconds, with a lateral spacing of a few meters. If the cross-stream distribution of backscatter intensity is graphed, sediment suspension in the stream is indicated for the period of crossing. For that period, the backscatter intensity provides better spatial indication of suspended-sediment distribution than can be obtained from sediment sampling at each of five points during a period of 20 to 30 minutes. By mapping backscatter-intensity contours along stream crossings or complex survey paths, we can infer changes in suspended-sediment distribution at intervals of a few minutes.

Although the backscatter intensity recorded by ADCPs may not be an ideal indicator of sediment concentration (Gartner, 2002), spatial analyses exploit existing ADCPs for velocity mapping and indications of sediment transport, to show that some good data are better than no excellent data. New strategies have been tested to interpret backscatter-intensity contours as maps of suspended-sediment distribution. These strategies employ techniques used to map flow fields and interpolate velocity data to three-dimensional grids (Dinehart and Burau, 2003).

Flow-field mapping and interpolation allow spatial analysis of changes in vector fields and suspended-sediment distributions from one ADCP survey to the next. The streambed is the local source of much suspended sediment, and multiple ADCP surveys obtain sufficient data to map streambed bathymetry from individual beam depths (Dinehart and Burau, 2003). By superimposing maps of backscatter intensity on the streambed bathymetry, the correspondence of spatial variations in suspended sediment with transient bed features becomes apparent. By plotting velocity vectors with color contours for backscatter intensity, the relation between local flow conditions and suspended sediment can be analyzed.

“Channel mapping” is a collective term chosen for the data processing and visualization of velocity, backscatter intensity, and bathymetry data from ADCPs in streams. The purpose of this short paper is to provide background on channel mapping so that some discrepancies between ADCP data and expected flow properties can be noted. Resolution of these discrepancies by experimental investigations will reduce the uncertainty associated with flow-field interpolations and enhance eventual calculations of sediment discharge from ADCP data.

DATA ACQUISITION AND PROCESSING

Operational characteristics of ADCPs have been described in technical manuals by RD Instruments (Gordon, 1996). Simpson and Oltmann (1993) adapted ADCPs from oceanographic applications to measure discharge in tidal channels with moving boats. The adaptation was accomplished by extensive testing in the Delta of the Sacramento and San Joaquin Rivers by the USGS (Simpson, 2001). The methods presented here were developed from analysis of ADCP surveys made in the Delta of the Sacramento and San Joaquin Rivers during 2000-2003, by the Bay-Delta Hydrodynamics Project of USGS (California District, supervised by Jon Burau), and by the author on behalf of the CalFed Sedimentation Project. The example data of ADCP surveys come from various broadband models manufactured by RD Instruments.

To obtain the ADCP surveys, flow-defining patterns were first drawn digitally on maps of reaches to be surveyed. The surveyed reaches were at tidal rivers and sloughs with sand beds and slow velocities (~1 meter per second or less). Navigational positions were provided by input from receivers for differential Global Positioning System (GPS) data. Pilots steered along patterns on the maps while watching their boat’s position plotted continuously by GPS. Tidal channels were surveyed repeatedly during daylight or through a diurnal tidal cycle. Data from multiple crossings at various distances along the reach were used to create three-dimensional vector grids over channel bathymetry. An alternate source of ADCP surveys for spatial analysis was obtained from routine ADCP discharge measurements made to calibrate ultrasonic velocity meters installed at gaging stations. Although the paths of the discharge measurements were too closely spaced in the channel to show longitudinal variations, the lateral resolution of velocity at the cross section was much higher than obtained by traditional stream-gaging methods. Time resolution also was much higher, as each measurement was completed in a few minutes, and repeated for as many as 12 hours.

Data-processing programs were written initially to analyze and display hundreds of ADCP surveys made at a channel junction of the Sacramento River (Dinehart and Burau, 2003). The programs (DopplerMacros) allowed channels to be surveyed repeatedly with ADCPs with minimal post-processing of survey data. Two commercial software programs were used together to extract and view output files from WinRiver (RD Instruments), a propriety software program for data acquisition and review of ADCP data. Program algorithms for processing ADCP data were written in Microsoft Excel with Visual Basic for Applications. Graphical procedures for spatial analysis were designed using Tecplot by Amtec, Inc.

Each vector of a velocity ensemble was measured by the ADCP at one of multiple depth cells. In the post-processing phase, velocity-ensemble data are inspected and filtered with several passes. The first pass through an ADCP survey removes empty ensembles and gross outliers near the bed. A second pass removes additional outliers at the bottom of each ensemble, which are usually attributed to ambiguity errors (Gordon, 1996). An optional third pass performs the only numerical changes to original velocity data. Vector components exceeding the mean of the ensemble by 2.5σ (standard deviation) are interpolated to the value of their nearest neighbors. This operation is followed by a centered, three-point average applied to all interior points of each ensemble (Fig. 1). As a final option, vectors in the velocity profile can be extrapolated from the remaining, bottom velocities to zero at the bathymetric surface. Outliers in ensembles of backscatter values were less common, and no special filtering is applied to them at this stage, although values can be extended linearly to the bed.

After ADCP data are registered to geographic coordinates and filtered, program scripts produced by Visual Basic for Applications automate the import of velocity and bathymetric data to Tecplot. Local bathymetry was mapped in Tecplot by interpolation of individual beam depths to regular mesh grids (Dinehart and Burau, 2003). The bathymetric data from ADCP surveys were sufficiently dense for definition of channel topography. With Tecplot, a shaded bathymetric surface can be displayed in the background while the overlying ADCP surveys are varied through time. Velocities were visualized over bathymetry by displaying vector ensembles colored according to vector magnitude or backscatter intensity. Alternatively, the vector origins were connected in vertical, curved planes and superimposed on bathymetry. When colored for backscatter intensity, the contoured planes over bathymetry indicated regions of sediment suspension or scour (Fig. 2). From these visualizations, users can assess the influence of flow conditions and streambed topography on mapped velocity vectors and backscatter intensity.

DISCREPANCIES NOTED BY SPATIAL ANALYSES

By comparing expected flow properties with spatial analyses of ADCP surveys, a number of discrepancies have been noted. They may come from the intrinsic ADCP operation or from the subsequent interpolations, but field research is necessary to resolve them before channel-mapping procedures become reliable for sediment-transport studies.

Mean velocity-vector components: To fill the gaps along flow directions between survey paths, velocity vectors were interpolated to mesh grids that conformed to local bathymetry and water surface (Dinehart and Burau, 2003). In this process, the interpolated flow directions were more coherent at adjacent nodes when the velocity ensembles were smoothed by the optional three-point average. However, velocity ensembles are collected over durations that can be an order of magnitude less than macroscale turbulence. Therefore, the uncertainty in vector directions is not necessarily reduced by smoothing these short-duration samples.

A central assumption of velocity measurement by ADCP is that scatterers in the flow move at the same horizontal velocity through all four sonar beams. Exceptions to this assumption are more substantial in alluvial channels than in the ocean because of the ubiquity of sediment suspension by macroscale turbulence throughout the water column. Mapping velocity while rapidly crossing a turbulent flow field, therefore, invites high uncertainty in vector components. This uncertainty increases when velocity ensembles recorded with single pings are used (Gordon, 1996).

Although velocity ensembles derived from multiple pings may mask the inclusion of ambiguity velocities, the net effect is that vector directions become more uniform. The spatial distance between transmitted ensembles does not increase proportionally with more internal averaging because ping intervals are short, relative to data-transmission intervals. The preference for single-ping ensembles in discharge measurements does not seem to be appropriate for flow mapping, because the high standard deviation induced by macroturbulence affects mean vector components. An accurate measure of vector components is essential when sediment flux is to be calculated with normal vectors at cross-sectional planes of interpolated grids. For these reasons, the various aspects of ADCP surveys that affect mean vector components require experimental investigation.

Backscatter intensity: A gross, direct correlation between backscatter and mean velocity can be documented for changes in river discharge from flood to ebb tide and from common to storm flows. This observation is consistent with expected sediment-transport relations. However, direct correlations are less apparent at shorter time scales, from 5 seconds to a few minutes. Instead, occasional increases in backscatter are often correlated with decreases in longitudinal velocity. The inverse correlations may originate from sediment suspended by upward bursts that have lower horizontal velocity. Accordingly, vector directions determined from movement of large, suspended scatterers may include effects of eddy boundaries, particle settling, and particle inertia.

As noted previously, discharge measurements by ADCP provide repeated cross-sectional views of velocity and backscatter distribution in a channel. Each measurement records a set of velocity ensembles that can be rotated to a linear cross section for grid analyses. Using color contours, the corresponding set of backscatter-intensity values can be displayed for each ADCP crossing (Fig. 3). Backscatter intensity varies widely across the section, and the distribution varies gradually through time. Zones where backscatter intensity is consistently higher are visible in the time series of crossings. Close examination shows that varying backscatter intensity is often associated with small, lateral gradients in vector components. This implies that backscatter intensity also may vary in response to macroscale turbulence. Evidence of spatial changes in sediment concentration to explain the backscatter variations is presently unavailable. Independent, high-frequency measurements of flow velocity and sediment concentration in the vicinity of ADCP beams can determine the dominant contributions to backscatter intensity recorded in natural streams.

FUTURE DIRECTIONS

A specialized software environment is being developed for processing and visualization of ADCP data. Time series of vector grids, based on ADCP surveys, are easily acquired at channel locations away from gaging stations, and should prove valuable to agencies. To help complete multiple surveys, data processing will be simplified for general users so that ADCP data can be visualized to compatible standards. Those standards will guide the filtering of errors from ADCP data, the preferred geographic coordinates to apply, the formats for data storage, and will assure compatibility of results from different ADCP surveys. Research on mapping velocity during rapid passage through macroscale turbulence will validate flow-field interpretations of ADCP data for velocity and sediment flux. Ultimately, calibrated relations (Deines, 1999; Gartner, 2002) may be derived for the interpolated grids of velocity and backscatter, from which sediment discharge can be computed. Deriving sediment discharge from interpolated ADCP data depends on the success of current research in calibration techniques (Gartner, 2002), and the experimental resolution of discrepancies between ADCP data and expected flow properties.

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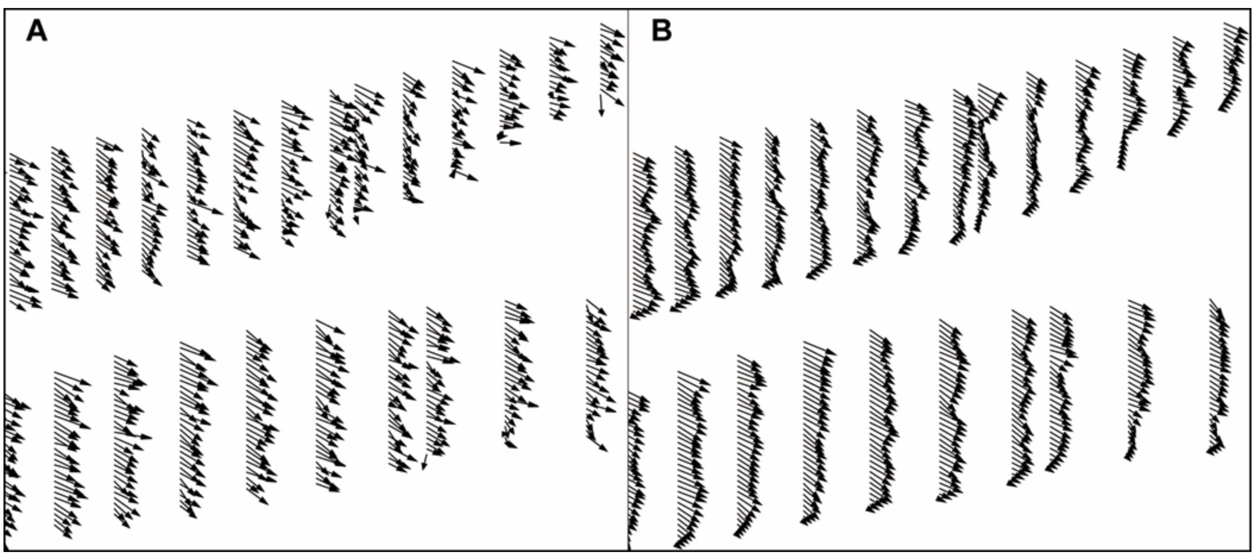

Figure 1. Oblique view showing velocity ensembles before (A) and after (B) outlier filtering. Velocity magnitudes range from 40 to 60 cm/s over mid-ensemble. Lateral distance between ensembles is about 1 to 2 m. Vertical distance between vector components is 0.25 m. Study site is Sacramento River at Walnut Grove, California, November 1, 2001.

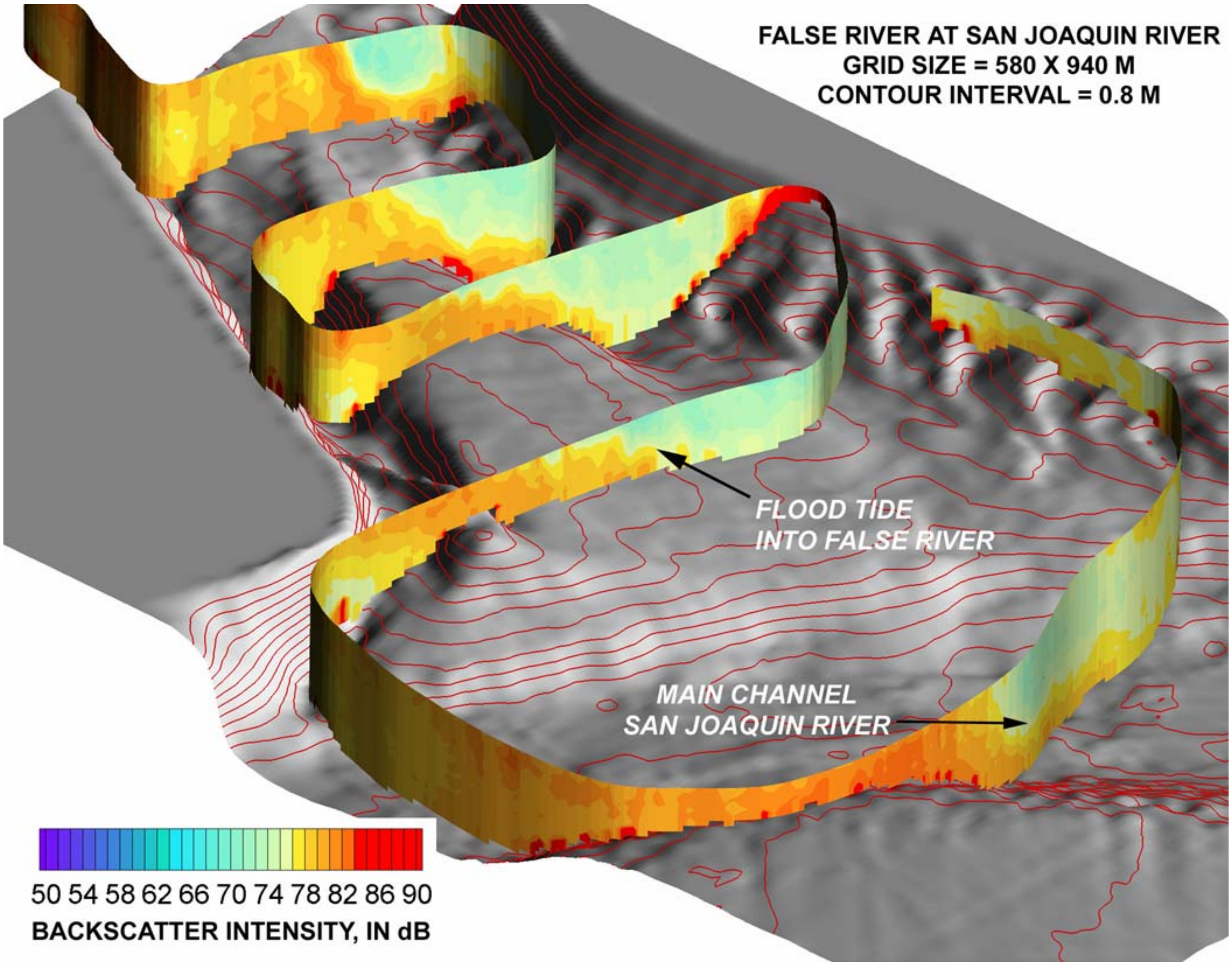

Figure 2. Oblique view showing backscatter intensity in planar contours over bathymetry. Backscatter intensity indicates regions of sediment suspension or eddy production. Colors are assigned to indicate range of backscatter intensity in decibels. Study site is False River at San Joaquin River, California, May 1, 2002. The bathymetry layer was interpolated from several ADCP surveys of area during study period.

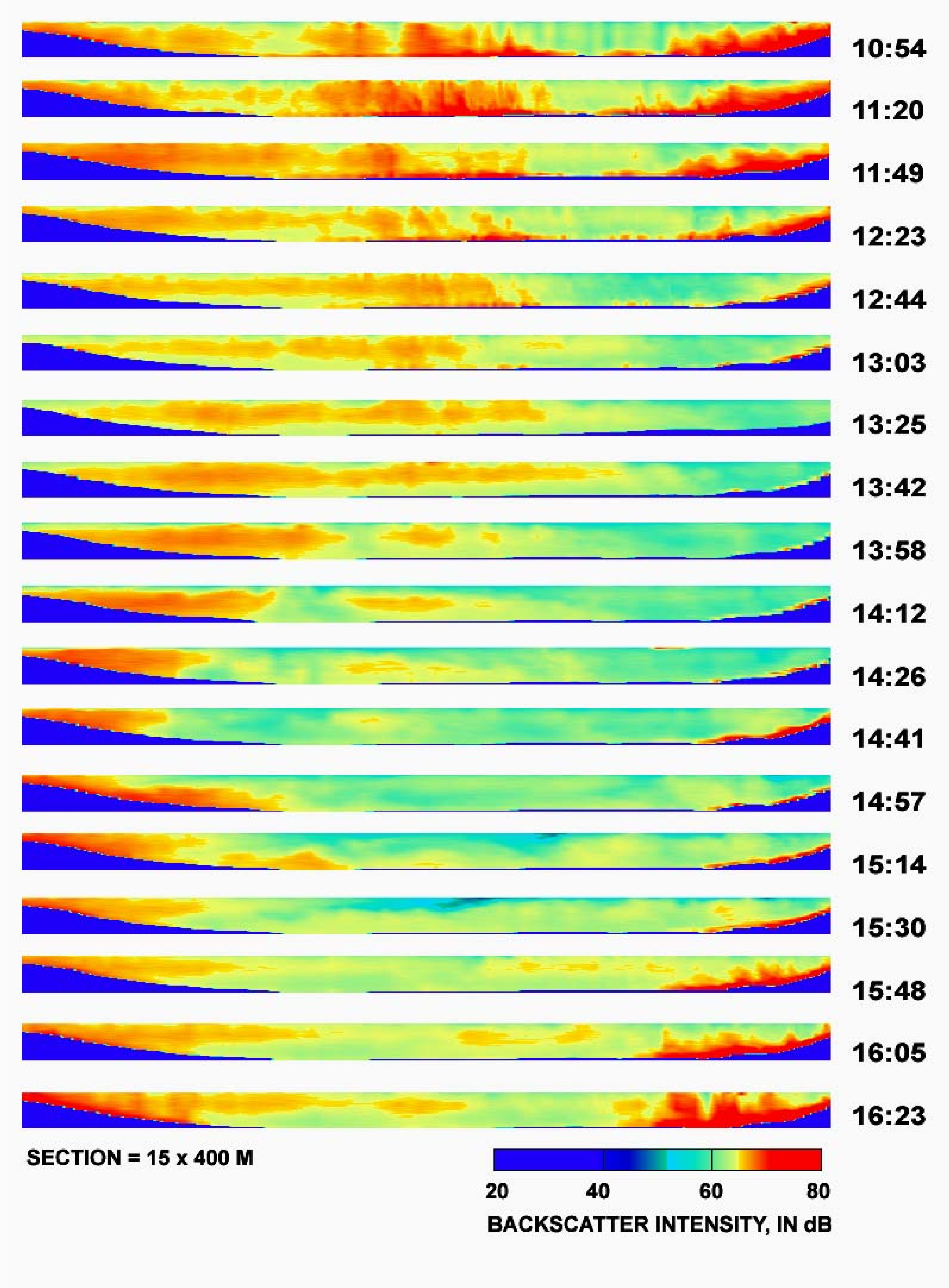

Figure 3. Elevation view showing sequence of backscatter-intensity plots from ADCP dischage measurements. Colors are assigned to indicate range of backscatter intensity in decibels. Study site is San Joaquin River at Jersey Point, California, March 14, 2001. Tidal flow ranges from ebb tide at top (toward viewer), to slack tide at 14:12, to flood tide at bottom (away from viewer).