AGU17 Poster

H11E-1222

US Army Corps of Engineers

Riverine Bathymetry Imaging with Indirect Observations

Jonghyun Harry Lee[1], Hojat Ghorbanidehno[2], Matthew W. Farthing[3], Ty Hesser[3] Eric E. Darve[2] and Peter K. Kitanidis[4]

[1]Civil and Environmental Engineering, University of Hawaii at Manoa, [2]Mechanical Engineering, Stanford University, [3]US Army Corps of Engineers ERDC-CHL, [4]Civil and Environmental Engineering, Stanford University

Overview

Bathymetry, i.e, depth imaging in a river, is of crucial importance for shipping operations and flood management. With advancements in sensor technology and computational resources, various types of indirect measurements can be used to estimate high-resolution riverbed topography. Especially, surface velocity measurements have been the object study because they are easy to acquire at a low cost in all river conditions and surface velocities are sensitive to river depth.
We image riverbed topography using depth-averaged quasi-steady velocity observations related to the topography through the 2D shallow water equations (SWE). The principle component geostatistical approach (PCGA), a fast and scalable variational inverse modeling method powered by low-rank representation of covariance matrix structure, is presented and applied to two "twin" riverine bathymetry identification problems. For comparison purposes, an ensemble-based approach is also applied to the test problems.

Principal Component Geostatistical Approach

With $\mathbf{m}$ unknowns, $\mathbf{n_{obs}}$ measurements, and forward model(s) $\mathbf{h}$, one needs:

- Jacobian matrix $\mathbf{H}$, *i.e.*, sensitivity of the data to unknown parameters $\frac{\partial \mathbf{h}}{\partial \mathbf{s}}$
- Jacobian products with the prior covariance matrix $\mathbf{Q}$, *i.e.*, $\mathbf{HQ}$ and $\mathbf{HQH}^\mathsf{T}$

For large-scale/joint inversions (large $\mathbf{m}$ and $\mathbf{n_{obs}}$), one faces several challenges such as

- time-consuming, invasive changes in multi-physics simulation code for efficient adjoint-state method implementation to evaluate Jacobian $\mathbf{H}$
- expensive Jacobian construction requiring $\mathbf{n_{obs}}$ ($\geq \mathcal{O}(10^4)$) simulations
- prohibitive large dense matrix multiplication/storage for large $\mathbf{m}$ ($\geq \mathcal{O}(10^6)$)

In order to tackle these challenges, we developed PCGA that avoids expensive Jacobian evaluation and its matrix products (cross-covariance) by using a **fast truncated decomposition** [2,3] of the prior covariance

$$\mathbf{Q} \approx \mathbf{Q}_\kappa = \Sigma_{i=1}^{\kappa} \zeta_i \zeta_i^\mathsf{T} \quad \Leftarrow \text{ scales linearly (Cost } \mathcal{O}(m\kappa^2))$$

and **finite-difference approximation**:

$$\mathbf{H}\zeta_i \approx \frac{1}{\delta}\left[h(\mathbf{s}+\delta\zeta_i) - h(\mathbf{s})\right], \quad \mathbf{HQ} \approx \Sigma_{i=1}^{\kappa} (H\zeta_i)\,\zeta_i^\mathsf{T} \quad \Leftarrow \text{ total } \kappa+1 \text{ simulations!}$$

Thus, PCGA can achieve **a significant speed-up with reasonable accuracy**, using simulation outputs **without modifying multi-physics simulation code**.

Case 1: Savannah River, GA

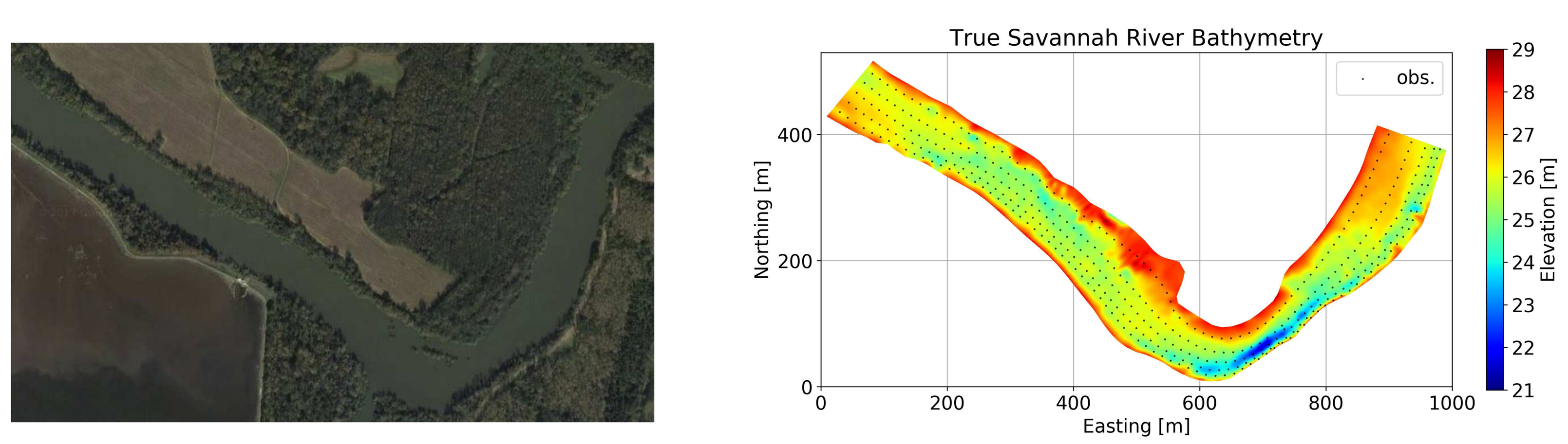

Figure: 1 mile reach of the Savannah River near Augusta, GA (left), and high-resolution bathymetry survey by U.S. Army Corps of Engineers (USACE) (right)

- The length of the domain is $\sim$ 1.2 km and across-channel distance is 98.4 m in avg.
- The river dynamics are simulated using the 2D shallow water module of the USACE's ADaptive Hydraulics (ADH) model [4].
- 20,541 unknown river elevation estimated from drift-measured velocity
- Forward simulations and inversions were executed on a 36 core workstation.

Results & Comparison with Ensemble-based method

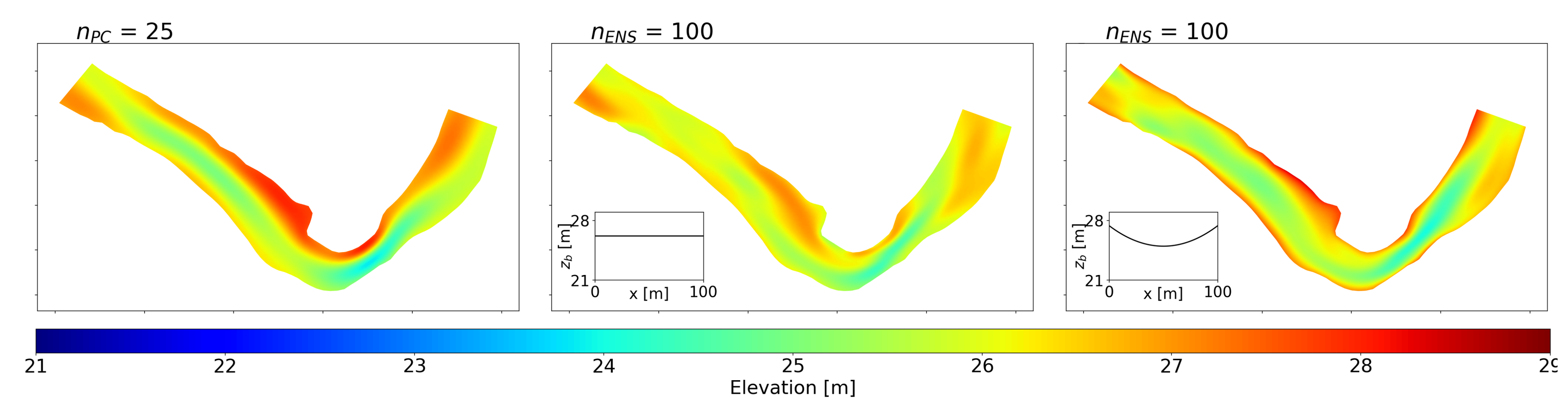

Figure: Estimate from PCGA (left), from ENS with a rectangular channel prior (middle), and from ENS with a parabolic channel prior (right)

Since eigenvectors of prior covariance matrix are the basis for the solution space of inverse problem [1] and eigenvalues indicate their importance, we investigate eigenvalues and eigenvectors used in PCGA and Ensemble-based approach

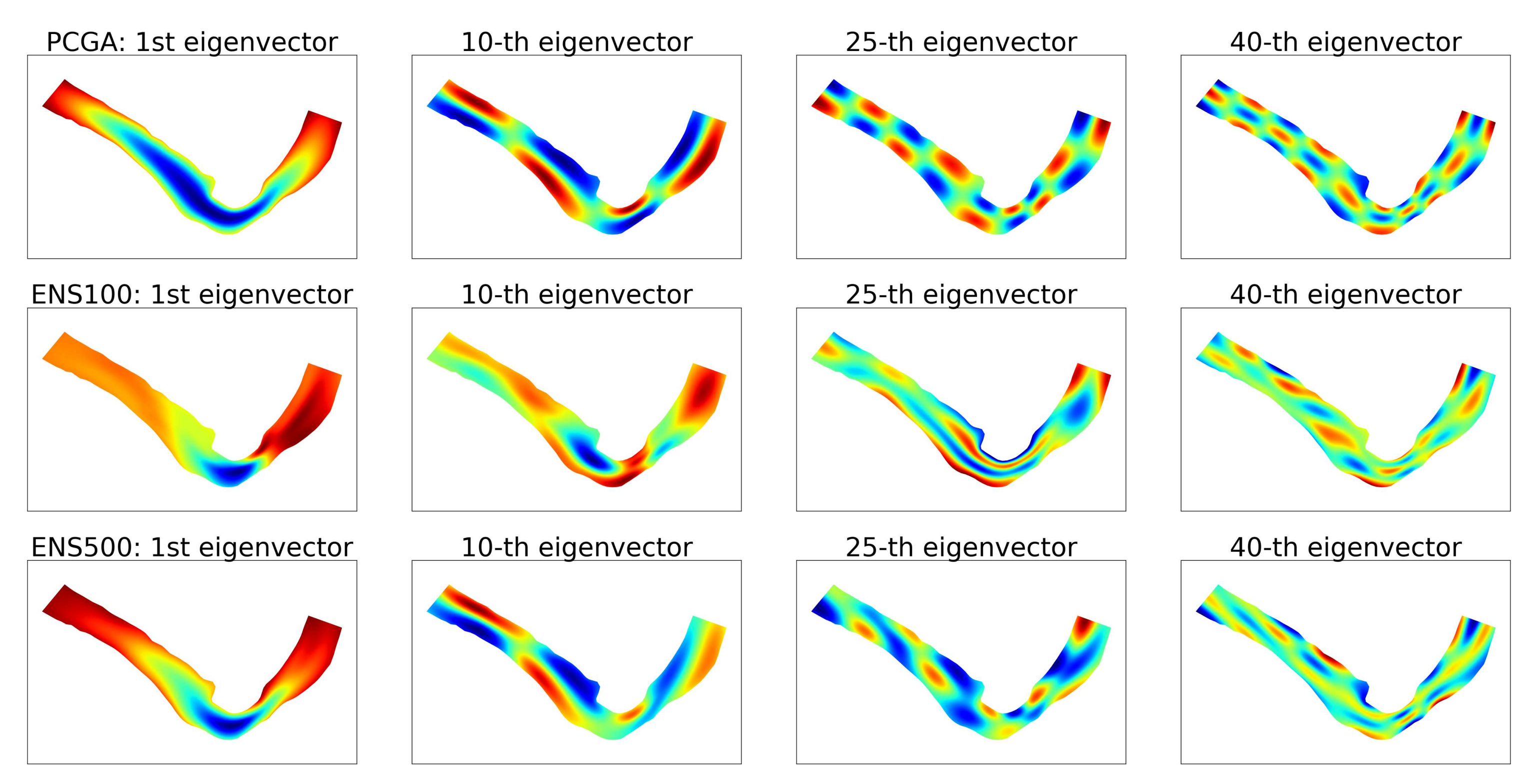

Figure: Eigenvectors of prior covariance matrix (top), a sample covariance matrix with 100 ensemble (middle), a sample covariance matrix with 500 ensemble (bottom)

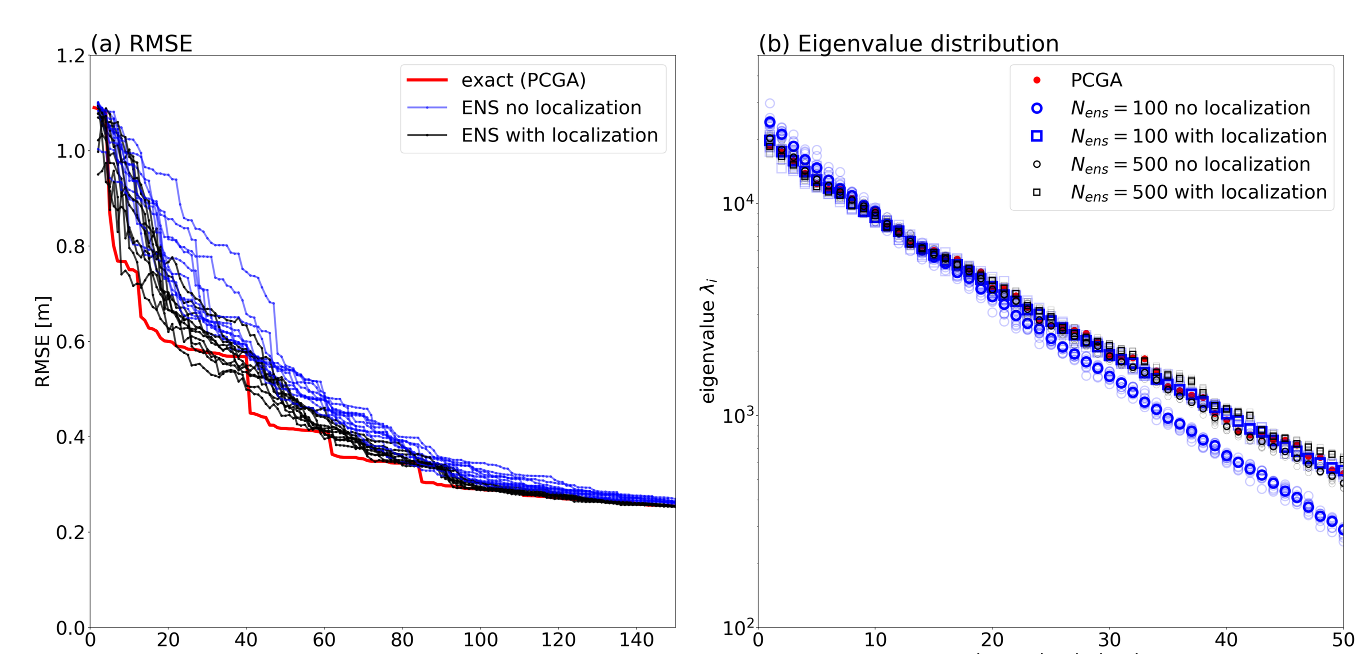

Figure: RMSE values between the true and projected riverine bathymetry of the Savannah River onto the eigenspace of the prior covariance vs. the number of rank used in PCGA (n_{PC}) and the ensemble-based method (n_{ENS}) (left), eigenvalue distribution of the actual covariance matrix (red), and the ensemble covariance matrices (right)

Case 2: American River, CA

- 10 km reach of the American River, CA
- 102,051 elevation point estimation using 16,978 velocity measurements
- Only $\sim$ 400 ADH simulation runs required

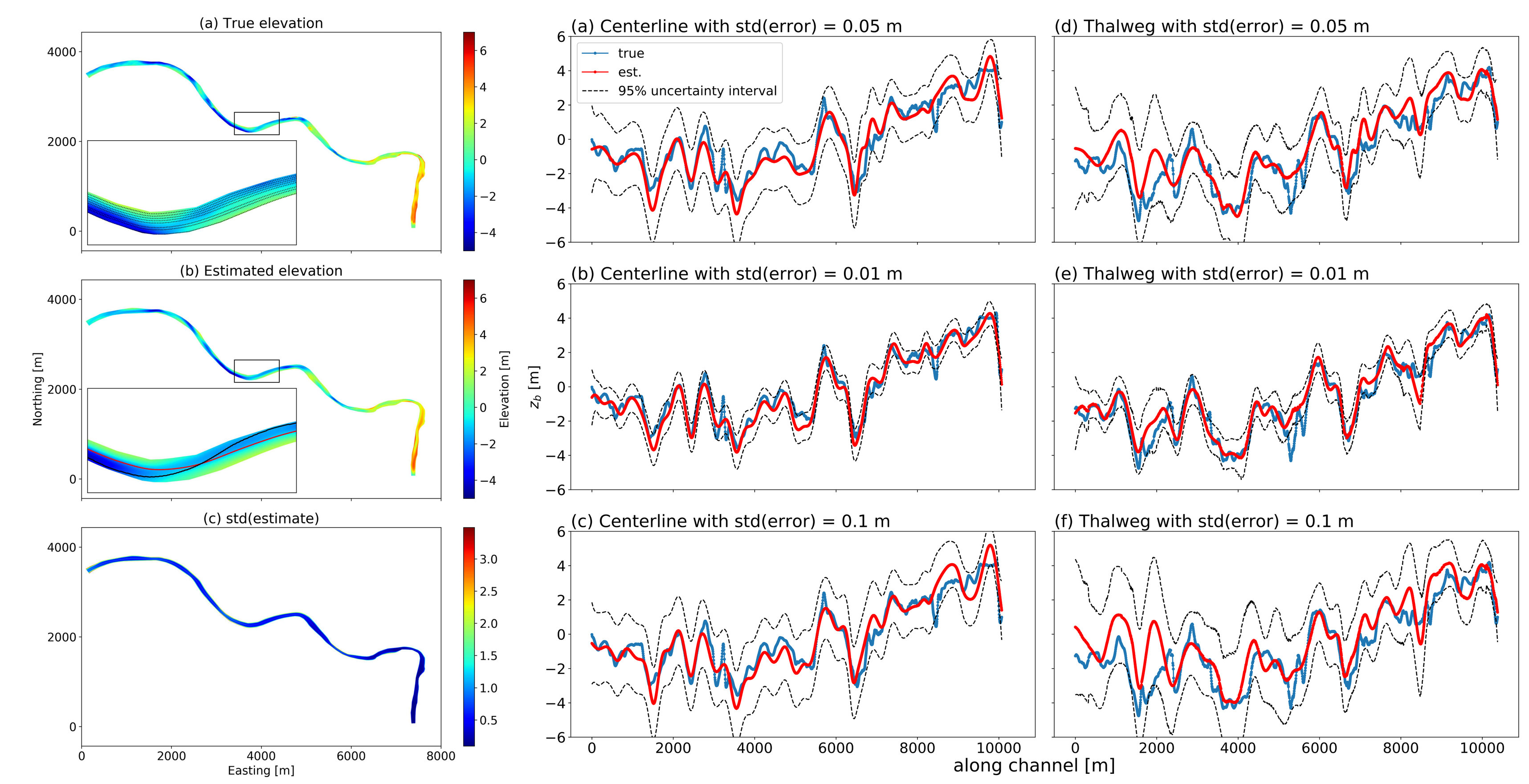

Figure: Bathymetry survey of American River, best estimate and estimation uncertainty (left) and Bathymetry estimates along the centerline (middle) and thalweg (right) with different level of observation error

Conclusion

- PCGA identifies small-scale river bottom features successfully with a relatively small number of the numerical model runs.
- Compared to an Ensemble-based approach (EnKF), PCGA is superior in accuracy for the same level of effort.
- The results obtained from PCGA do not depend on the initial guess.

Ongoing Works

- River bathymetry imaging at a tidal inlet near Puget Sound
- Software release - pyPCGA

References

For more info: www2.hawaii.edu/~jonghyun

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Acknowledgment

This work was supported by the Army High Performance Computing Research Center (AHPCRC, sponsored by the U.S. Army Research Laboratory under contract No. W911NF-07-2-0027) at Stanford University. Jonghyun Lee was supported in part by an appointment to the Postgraduate Research Participation Program at the U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory (ERDC-CHL) administered by the Oak Ridge Institute for Science and Education through an interagency agreement between the U.S. Department of Energy and ERDC. Jonghyun Lee was also supported by Hawai'i Experimental Program to Stimulate Competitive Research (EPSCoR) provided by the National Science FoundationâĂŹs Research Infrastructure Improvement (RII) Track-1: 'Ike Wai: Securing Hawai'i's Water Future Award #OIA-1557349. The computing resources for this project were provided under the AWS Cloud Credits for Research Program. Permission was granted by the Chief of Engineers to publish this information