SWOT Satellite Mission: Combined State Parameter Estimation

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Outline

- Surface Water Ocean Topography (SWOT) satellite mission
- The state-parameter estimation problem
- Data assimilation experiments
  - Water depth
  - Discharge
  - Channel width
  - Roughness coefficient
Need for a surface water mission

- Importance to hydrology – gauge measurements insufficient
- Temporal and spatial variability in water storage, river discharge
- Complexity of wetlands/oceans and river hydraulics
Global gauge measurements

All 7,222 GRDC river discharge gauging stations (monthly data including data derived from daily data), 264,743 station years (Status: 24 March 2005)
These surface water elevation measurements are entirely new, especially on a global basis, and thus represent an incredible step forward in hydrology.

- Ka-band interferometric system with 2 swaths
- SRTM heritage
- Produces heights and all-weather imagery
- Resolution: 2 m in azimuth and 10-60 m in range
SWOT not "gauging from space"

- SWOT images a swath on either side of the satellite track in addition to nadir altimeter profile
- Profiling altimeter tracks separated, limiting spatial scales

- Using a radar altimeter, 32% of rivers and 72% of lakes are not sampled
- 120 km swath, 16-day repeat would sample entire globe
Potential measurements

Measurements required:

\[ h \frac{\partial h}{\partial t} + \frac{\partial h}{\partial x} A = q - \frac{\partial Q}{\partial x} = L \frac{\partial h}{\partial t} \]
SWOT implications

- Freely available data on water storage for water bodies larger than ~1 km
- Capability to produce discharge data for rivers with width > ~50-100 m
- Global mapping of lakes and wetlands
- Water resources management (reservoir storage) & Trans-boundary issues
- Major implications for human health (e.g. malaria)
- Ability to predict floods and droughts
River discharge estimation

- Swath altimetry provides measurements of water surface elevation but not discharge (key flux in surface water balance)
- Satellite dataset, spatially and temporally discontinuous
- Data assimilation offers potential to merge information from SWOT with discharge predictions from river hydrodynamics models
- Role of model uncertainties and potential for estimating model parameters from assimilating satellite observations
Problem description

• Combined state-parameter estimation
• Typically done with model calibration
  – Assumes model is perfect except for errors in parameters

• Data assimilation can find the PDF of both the parameters and associated model solution conditioned to a set of measurements
Bayesian formulation

\[ \frac{\partial \psi}{\partial t} = g(\psi, \alpha) + q \]  
Model equation

\[ \psi|_{t_0} = \Psi_0 + a \]  
Initial condition

\[ \psi|_{\partial D} = \psi_b + b \]  
Boundary condition

\[ \alpha = \alpha_0 + a' \]  
Poorly known parameters

\[ M(\psi, \alpha) = d + \epsilon \]  
Measurement equation

Baye's theorem

\[ f(\psi, \alpha, \psi_0, \psi_b | d) \propto f(\psi | \alpha, \psi_0, \psi_b) f(\psi_0) f(\psi_b) f(\alpha) f(d | \psi, \alpha) \]
Ensemble methods

- Assume that prior densities are Gaussian and model is a first-order Markov process

\[ f(\psi_1, \ldots, \psi_k, \alpha, \psi_0, \psi_b | d) \propto f(\alpha) f(\psi_0) f(\psi_b) \prod f(\psi_i | \psi_{i-1}, \alpha) \prod f(d_j | \psi_{i(j)}, \alpha) \]

- Can use ensemble representation for PDFs

Ensemble Kalman Smoother

Ensemble Kalman Filter
Experimental design

Baseline Meteorological Data → Hydrologic Model → Baseline Boundary and Lateral Inflows

Baseline Model Parameters → Hydrodynamic Model

Baseline Water Depth and Discharge → JPLWatER Simulator

Updated Water Depth, Discharge, and Parameters → "Observed" WSL

Perturbed Water Depth and Discharge → Kalman Filter

Perturbed Model Parameters
Hydrology/Hydrodynamics models

- Variable Infiltration Capacity model to provide the lateral and upstream boundary inflows
- Has been applied successfully in numerous river basins
- LISFLOOD-FP, a raster-based inundation model
- Based on a 1-D kinematic wave equation representation of channel flow, and 2-D flood spreading model for floodplain flow
Study area and implementation

- Ohio River basin
- Channel length ~1000 km
- 270 m spatial resolution
- 20 sec time step
- 4-month simulation (1 Jan – 28 Apr 1995)
- Truth simulation using nominal model parameters: channel width and roughness coefficient
- Errors introduced for both open-loop and filter simulations
Sensitivity to channel width

- Perturb channel width and evaluate sensitivity of simulated water depth and discharge
Sensitivity to channel roughness

- Perturb Manning's $n$ and evaluate the sensitivity of simulated water depth and discharge

Channel Water Depth

Channel Discharge Differences
Model parameter errors

- Channel width is linearly interpolated between upstream and downstream boundaries
- Roughness coefficient spatially uniform in the channel and floodplain
- Prior PDFs from sampling Gaussian distributions
  - $N(1.1 \, W_n, \, 10.0)$ for channel width
  - $N(0.06, \, 0.015)$ for Manning's $n$
- No errors in upstream or lateral boundary inflows
Ensemble Kalman Filtering

- Square root low-rank implementation
- Avoids measurement perturbations
- State vector augmented with model parameters
- Pre-conditioning (scaling) for numerical stability
SWOT observations

- NASA JPL Instrument Simulator
- Provides “virtual” observations of WSL from LISFLOOD simulations
- 50 m spatial resolution
- ~8 day overpass frequency
- Spatially uncorrelated errors
- Normally distributed with zero-mean and 20 cm standard deviation
Results – Water depth

- Water Depth (in meters) maps for different simulations on 13 March 1995 (06:00)

TRUTH

TRUTH – OPEN LOOP

TRUTH – FILTER
Results – Channel WSL

- Channel water surface elevations (in meters) for the different simulation during update times

13 March 1995 - 06:00

22 April 1995 - 06:00
Results – Channel discharge

- Channel discharge (same dates) profiles
- Calculated from Manning's equation in the model, with uncertain width, roughness and depth

13 March 1995 - 06:00

22 April 1995 - 06:00
Channel width estimation

- Linearly interpolated channel width explicitly built into filtering algorithm
- Spatial map of true width and channel profile of surface width after update (13 March 1995)
Roughness coefficient estimation

- Time series of roughness coefficient estimate
- Ensemble values for two updates
- Smoothing may be more appropriate
Future research

- Data assimilation provides opportunity to simultaneously estimate water depth and discharge along with river morphological parameters
- Additional experiments
  - Spatially variable channel roughness
  - Include errors in upstream and lateral boundary inflows
  - Other study areas (Amazon & Peace-Athabasca)
  - Synthetic cases of low flow and flood inundation
Questions?