Basin-wide data assimilation of SWOT observations: Initial results

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Motivation

- SWOT *direct* observations will include **water surface elevations**, **widths** and **slopes**
- Discharge is very important for hydrology
- Direct estimation of discharge through Manning's equation can be difficult
- Models can predict discharge, but impeded by significant errors
  - Forcings (e.g. precipitation, boundary inflows)
  - Model parameters (e.g. channel characteristics)

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- Models can predict discharge, but impeded by significant errors
  - Forcings (e.g. precipitation, boundary inflows)
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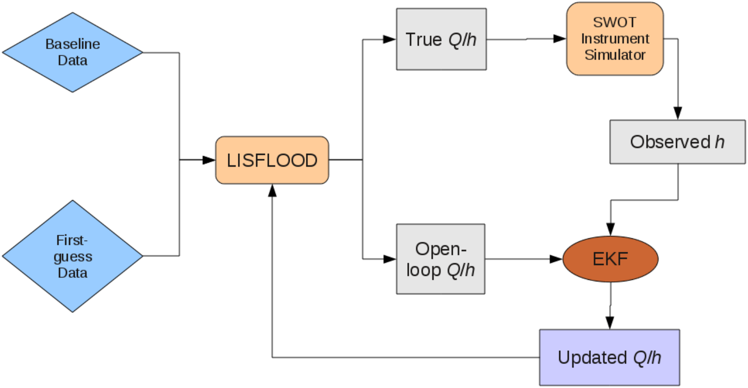
- Merging SWOT observations with modeling predictions via data assimilation
- Developing and testing of SWOT assimilation framework for discharge estimation

How to test the algorithms?

- “Virtual” SWOT observations
- Identical twin synthetic assimilation experiment

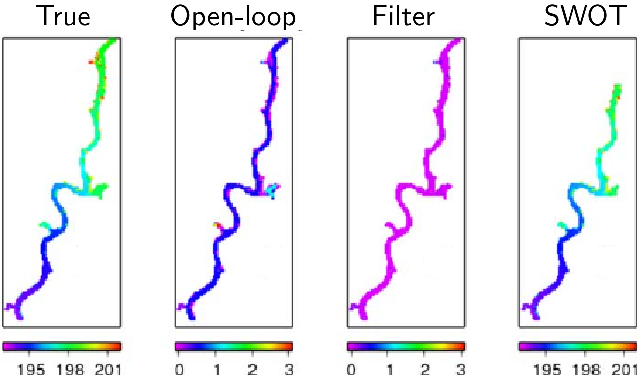


Previous work

- A number of simple data assimilation experiments in different study areas
- Amazon River basin
  - 240 km reach
  - Relationship between inundated area and slope
  - Estimated WSE and bathymetry at selected locations
- Ob River basin
  - Estimated water depths
  - Model errors in precipitation and temperature
  - Demonstrated effects of localization in assimilation
- Ohio River basin
  - 50 km reach
  - Assimilation of SWOT WSE to estimate river discharge
  - Examined sensitivity to observation error and temporal persistence of analysis

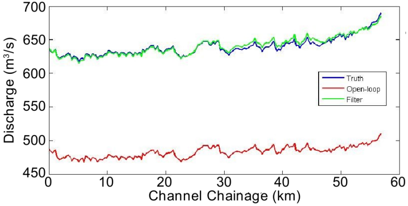
Previous work - WSE

- Estimated river channel discharge and water depth after assimilating synthetic WSE observations
- True and Observed WSE
- Differences of Open-loop and Assimilated WSE, from the True WSE

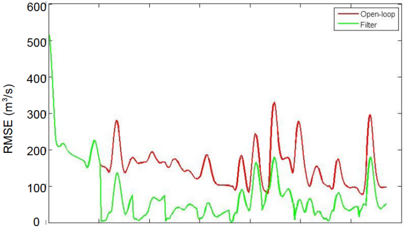


Previous work - Discharge

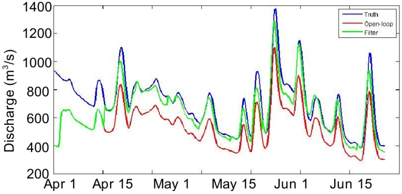
Along-channel discharge

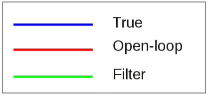


Discharge error time series



Downstream discharge



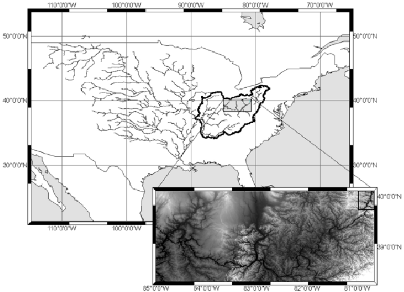


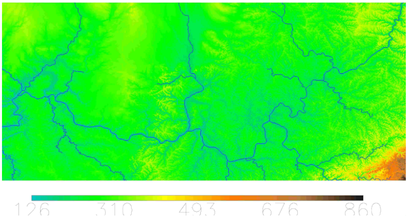
Previous work - Limitations

- Model errors came only from boundary inflows
- Uncertain knowledge of channel characteristics (bed elevation, roughness etc.)
- Synthetic SWOT observations generated by adding white noise ($\sigma = 50\mathrm{cm}$) to "true" WSEs
- Needed an actual SWOT instrument simulator to produce synthetic observations with correct *orbital* and *error* characteristics
- Larger domain size simulations

Study area

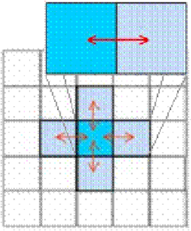
- ∼1000 km reach of the Ohio River basin
- Drains an area of ∼220,000 km^2
- Topography from National Elevation Dataset (30 m)
- River topology from HydroSHEDS
- Channel width and depth from developed power-law relationships
- Modeled main stem with inflows from tributaries

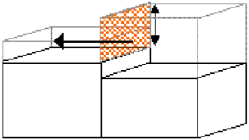




- LISFLOOD-FP raster-based hydrodynamics model
- 1-D solver for channel flow
- 2-D flood spreading model for floodplain flow
- Kinematic, Diffusive and Inertial formulations
- Requires information on topography, river channel characteristics and boundary inflows

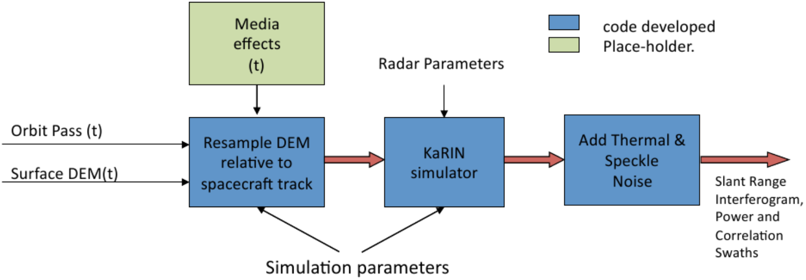
- Assumption of rectangular channel
- Has been successfully applied in a number of river systems (mostly smaller scale)





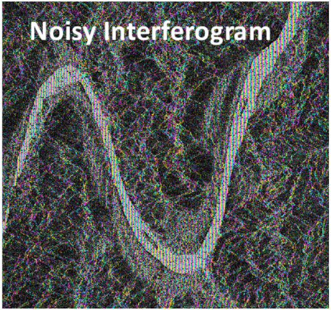
SWOT simulator

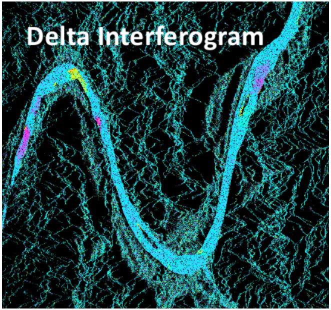
- The Instrument Simulator calculates interferometric response from land and water
- Produces data with correct SNR, layover and geometric decorrelation scattering properties
- Thermal and speckle noise are added
- Media effects will be added (precipitation, wet tropospheric delay)



SWOT simulator data processing

- Topographic layover and low land SNR make conventional phase unwrapping challenging
- Fringes are well defined over the water
- The signal from topography may contaminate the signal over the water
- Assuming a “reference” interferogram, a change in height can be estimated





Open-loop simulation

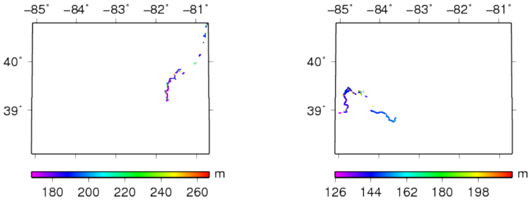
- 3-month simulations
- Boundary inflows taken from USGS gauge measurements
- Perturbed for "first-guess" using $\widehat{Q} = Q + N(0.2\,Q, 0.3\,Q)$
- Can examine impact of model errors in inflows and channel characteristics separately
- Channel width perturbed with 10% zero-mean Gaussian errors
- Channel bathymetry perturbed with Gaussian errors N(2.0m,0.5m)
- Roughness coefficient assumed to be 0.042 (true value of 0.030)
- Three open-loop simulations (Q, wnz, wnz-Q)

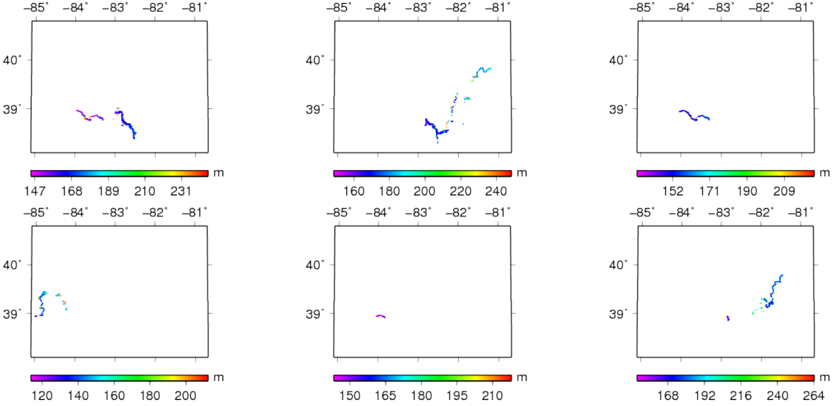
Data assimilation

- A number of assimilation techniques available
- Extended Kalman filter (EKF)
  - Requires explicit modeling of model error covariance, and tangent linear models
- Ensemble Kalman filter (EnKF)
  - Requires ensemble of model states
- EKF is used, estimating the model error covariances using the NMC method
  - assumes error correlations are similar to correlations of differences between successive forecasts
- Every SWOT pass is assimilated separately (filtering)
  - Smoothing could be done by assimilating observations for every orbit cycle

Results - SWOT observations

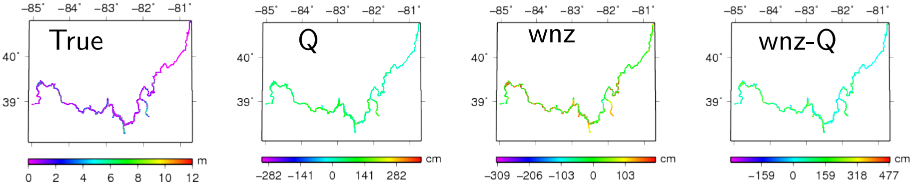
Successive passes of
a full orbital cycle



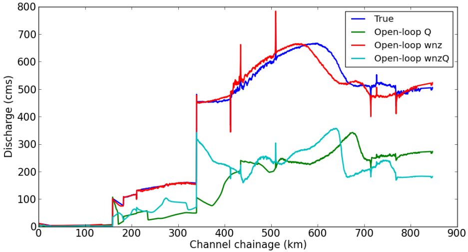


Results - Open-loop simulations

- True water depth and differences of three open-loop simulations from truth

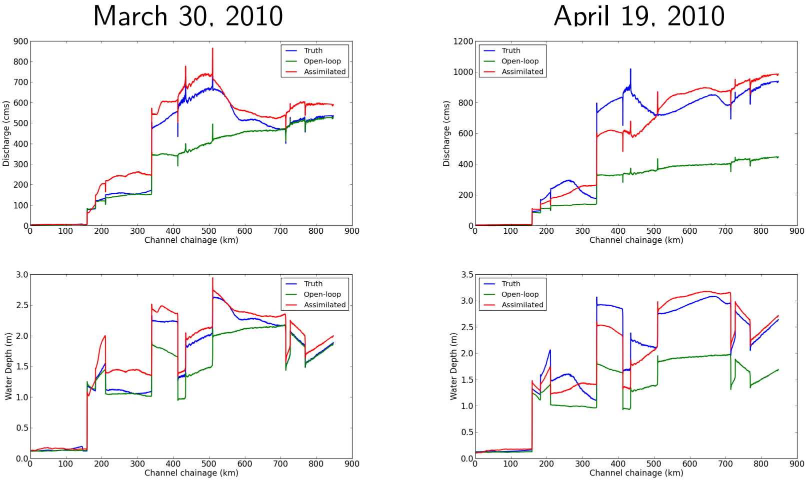


- Channel discharge for one time step
- Inflow error dominates simulated discharge
- Errors in channel characteristics play a less significant role



Results - Q Simulation

- Errors only in boundary inflows
- Discharge and water depth for the three different simulations



Results - wnz Simulation

- Errors only in channel width, depth and roughness
- Discharge and water depth for the same SWOT overpasses

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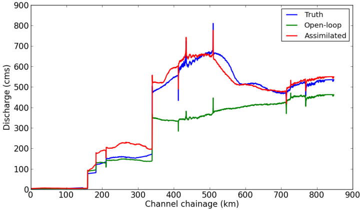

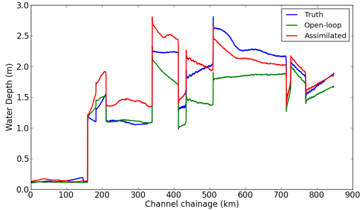

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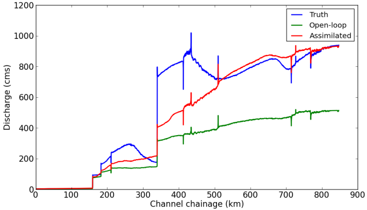

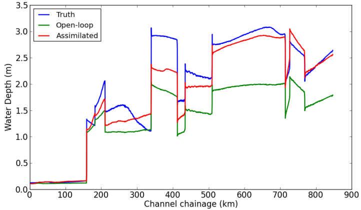

Results - wnz-Q Simulation

- Errors only in inflows as well as channel characteristics
- Ingesting SWOT observed WSE results in improved discharge estimates

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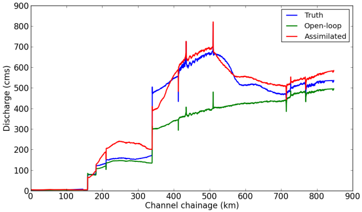

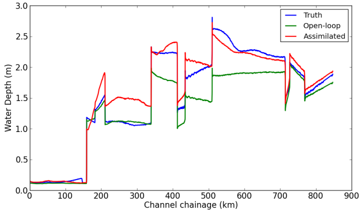

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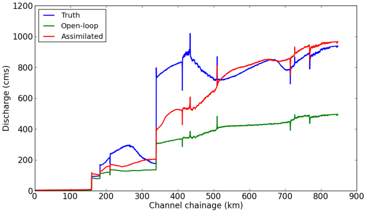
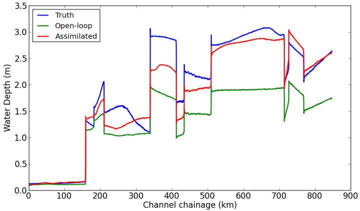
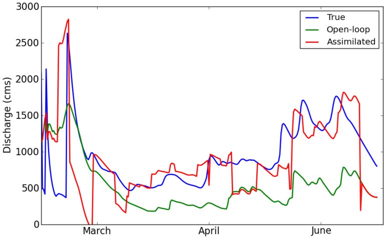


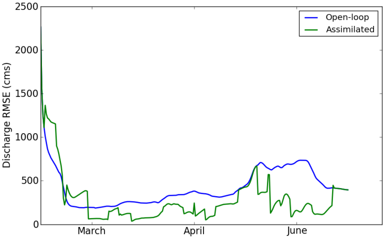


Discharge error temporally

- Comparison of predicted discharge at study basin outlet
- Spatially averaged error along the river channel
- Assimilated discharge estimates are clearly better
- Issue with temporal persistence, related to inflow errors



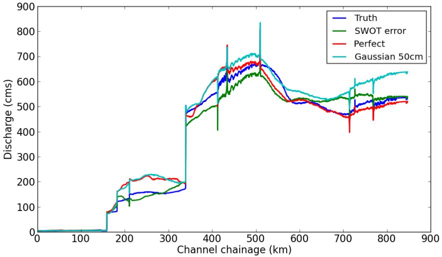
Downstream discharge

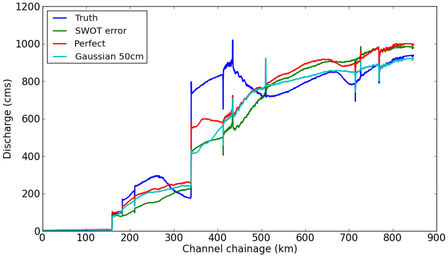


Discharge RMSE

Results - Observation error

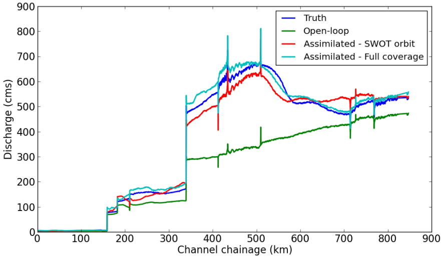
- SWOT WSE observations have an uncertainty estimate associated with each value
- During the assimilation, an estimate of that uncertainty is required
- We can assess the impact of different assumptions about the statistics of the observation errors

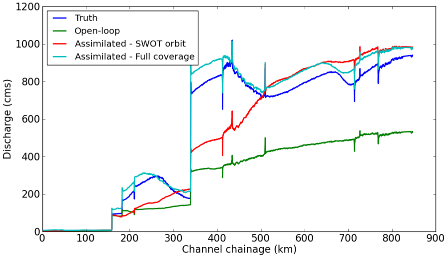




Results - Spatial coverage

- SWOT will observe the entire domain over a number of passes during the 22-day orbital cycle
- How much is the estimation skill decreased when compared to observing the entire domain “at once”?
- The assimilation is mostly able to compensate for partial spatial coverage





Practical issues

- Forward modeling (hydrodynamics) is computationally expensive
  - Multi-core/GPU computing
- Data assimilation algorithms
  - Can we afford ensemble-based approaches?
  - Variational assimilation
- Data processing
  - Very large volumes of data ($\sim$50 GB single SWOT cycle for the Ohio study area)
  - Massively parallel frameworks, e.g. Google's Map/Reduce or Hadoop
  - Different approaches for efficient storage and access (e.g. R-trees)

Conclusions

- Assimilation of SWOT observations overcomes errors in both inflows and channel characteristics
- Need extensive testing of different approaches in assimilating observations and modeling errors
- One important goal is creating algorithmic framework that
  - will be used for other study areas
  - can be released to the broader scientific community
- Assumptions for the observation errors, and the spatial coverage of SWOT do not appear to hinder discharge estimation

Ongoing & future work

- Explicitly model tributaries
- Fraternal twin assimilation experiment
  - A full St. Venant equation solving model (BreZo) to represent "truth"
  - LISFLOOD as the core of the assimilation system
- Evaluate different assimilation techniques and error covariance modeling approaches
- Assimilate additional SWOT observables (top width, slopes)
- Evaluate information content of SWOT observations
  - Estimate river channel bathymetry
  - Calibrate hydrodynamic and hydrologic models