PlumeSim
A simulation approach to autonomous adaptive plume tracking with multiple AUVs

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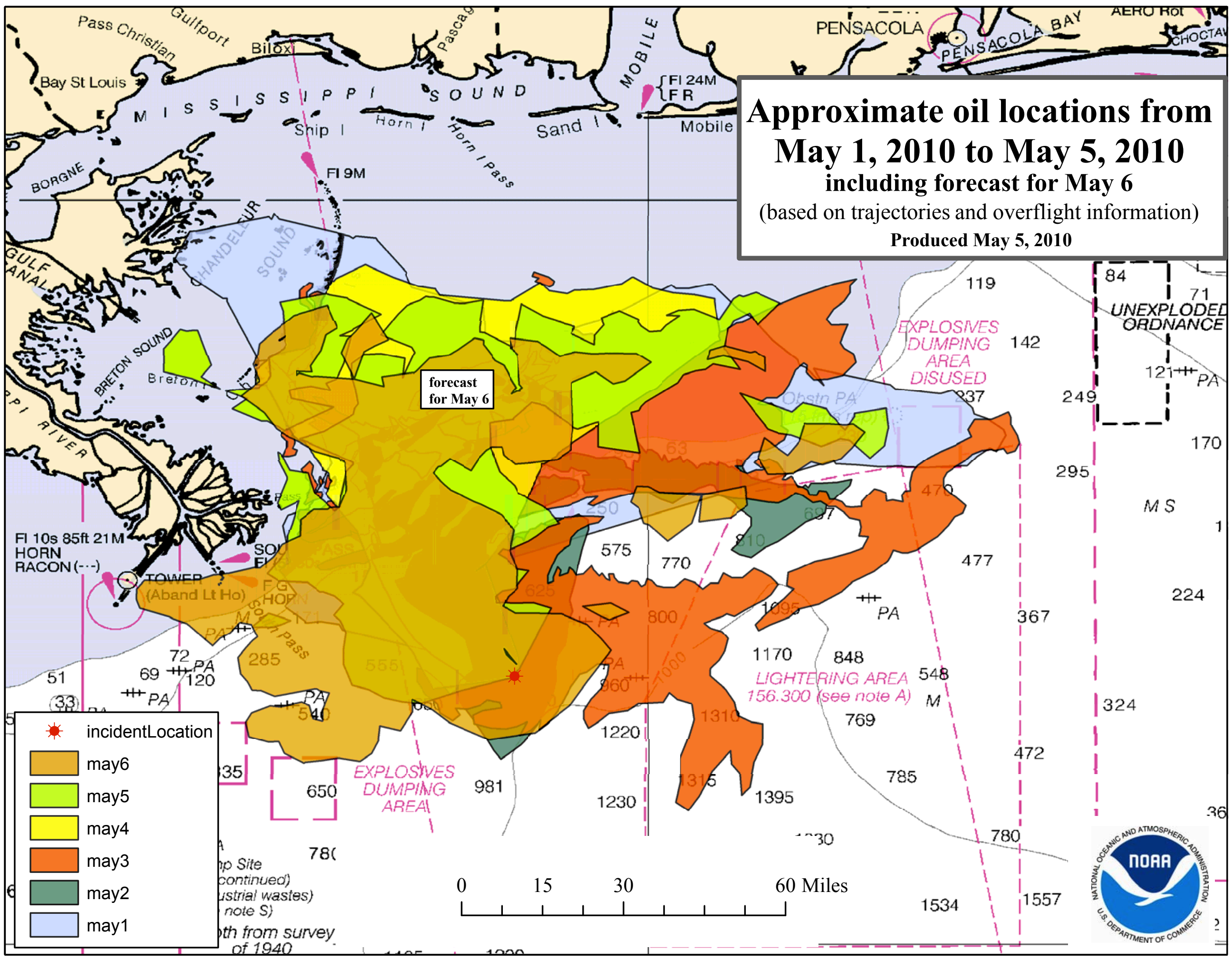
Goals

- Simulate a plume's shape as a sum of Fourier orders
- Sample the plume boundary with multiple AUVs
- Reconstruct the plume shape from AUV sample points
- Incorporate navigation errors & temporal variation
- Analyze errors between simulated plume and AUV-estimated plume

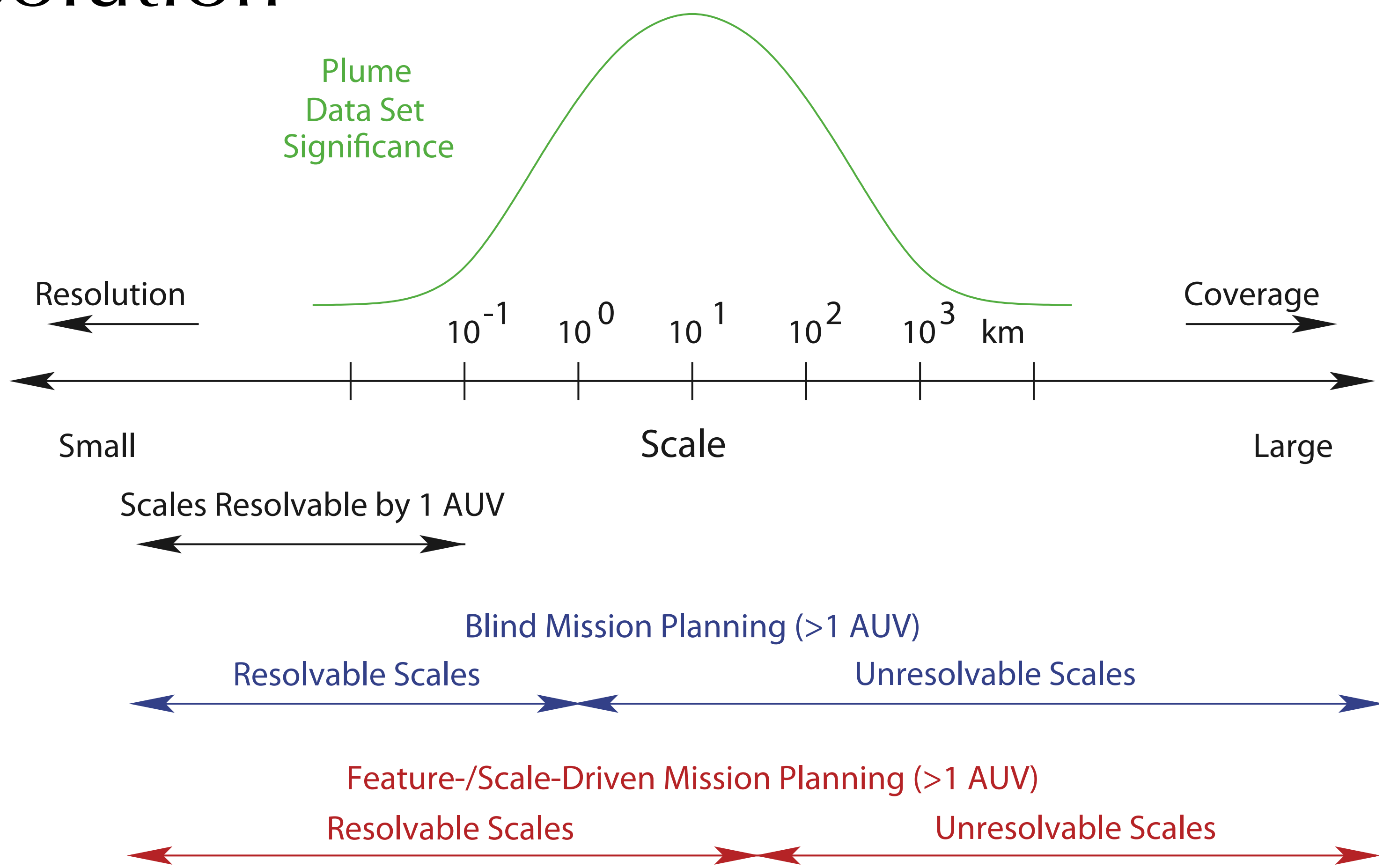
Motivation

- Predict & track hazardous underwater plumes: oil spills, harmful algal blooms, etc.



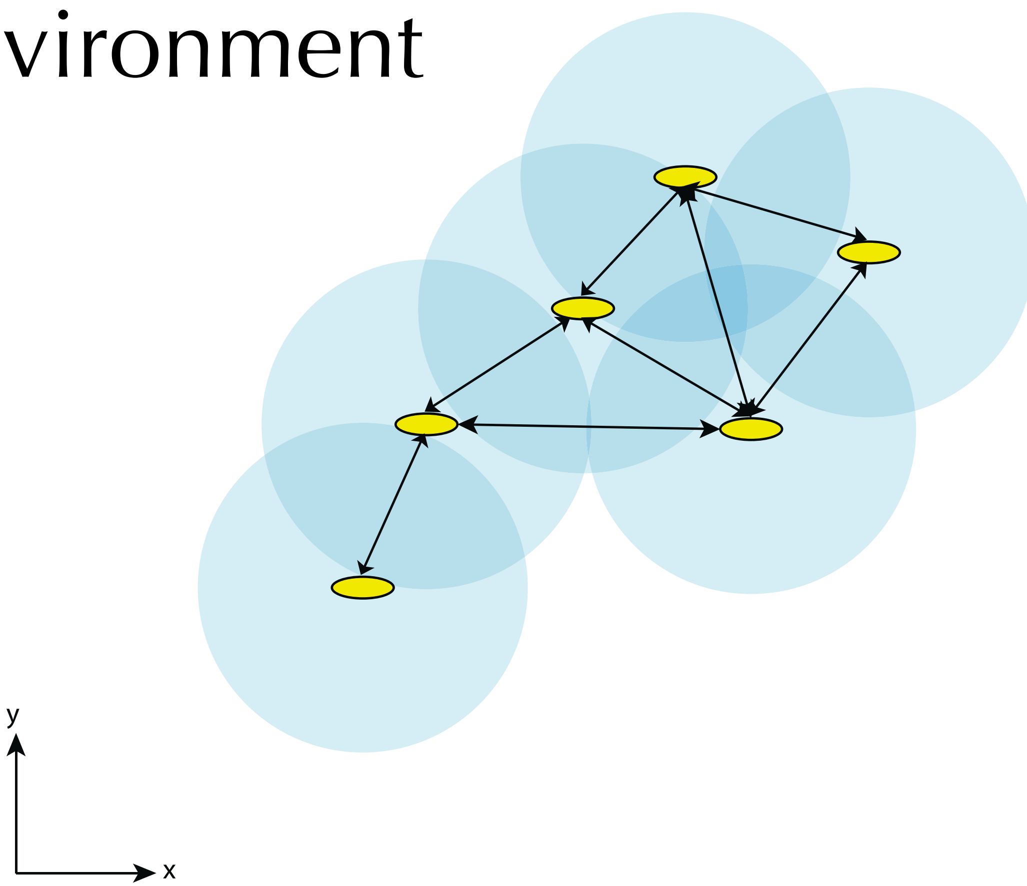
Motivation

- Spatiotemporal aliasing problem (large plumes, small AUVs), coverage vs. resolution



Motivation

- Make use of recent developments in AUV communications & autonomy to enable multi-AUV sensing of the ocean environment



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‘Actual’ Plume Construction: Sum of Fourier Orders

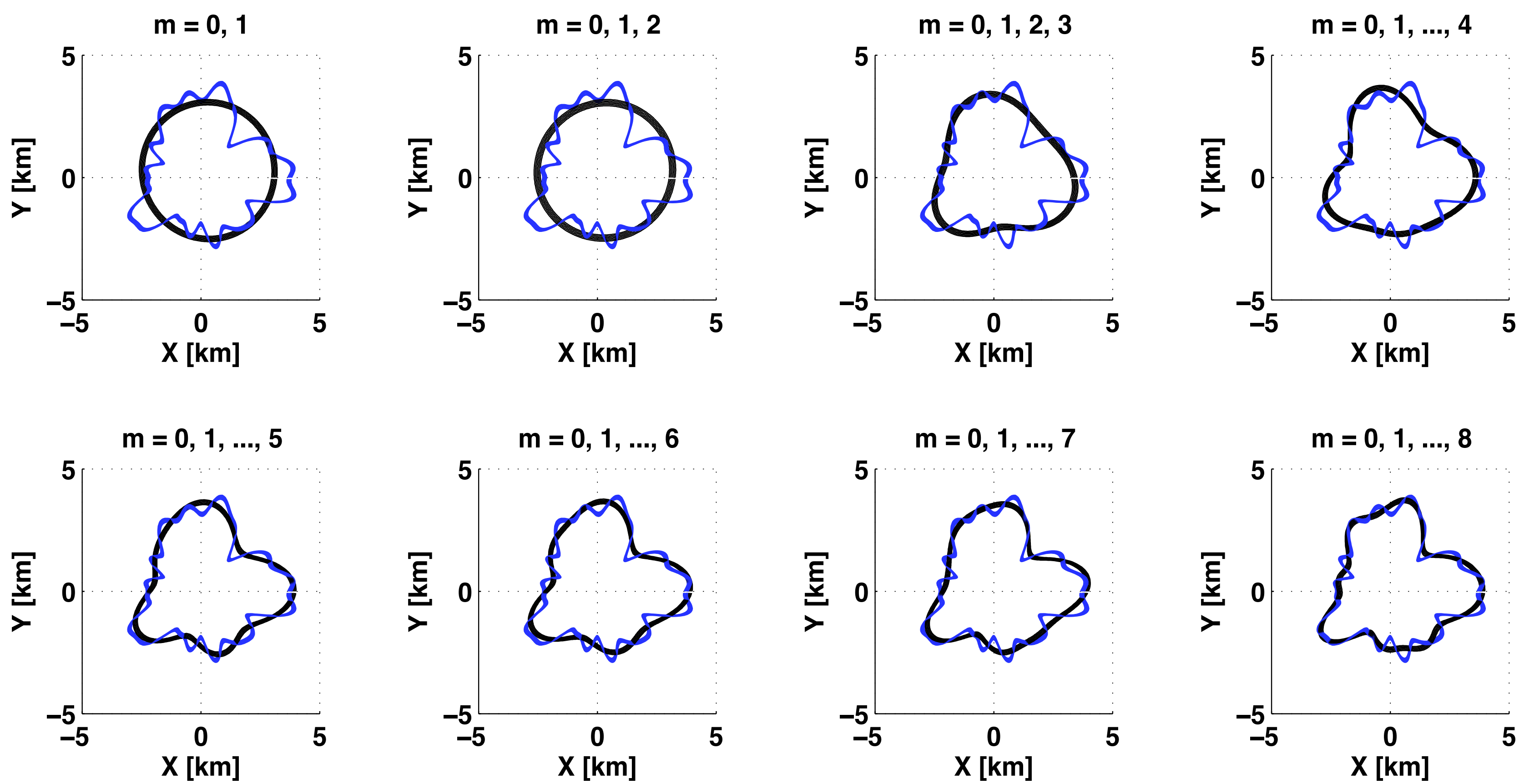
$$\Phi_M = \Sigma_{m=0}^{M} [A_m * cos(m\theta + \phi_m)] + R, \qquad (1)$$

- Construction in polar coordinates
- M = max # or Fourier orders
- $\Phi_M(\Theta)$ = radial distance of plume boundary from the origin at azimuth angle Θ
- Θ = azimuth angle about the plume origin
- R = radius of plume before perturbation
- A_m = amplitude perturbation for order m (random, bounded to 20% of R)
- ϕ_m= phase perturbation for order m (random, on $[0,2\pi)$)

Simulated Plumes

'Actual' plume construction:

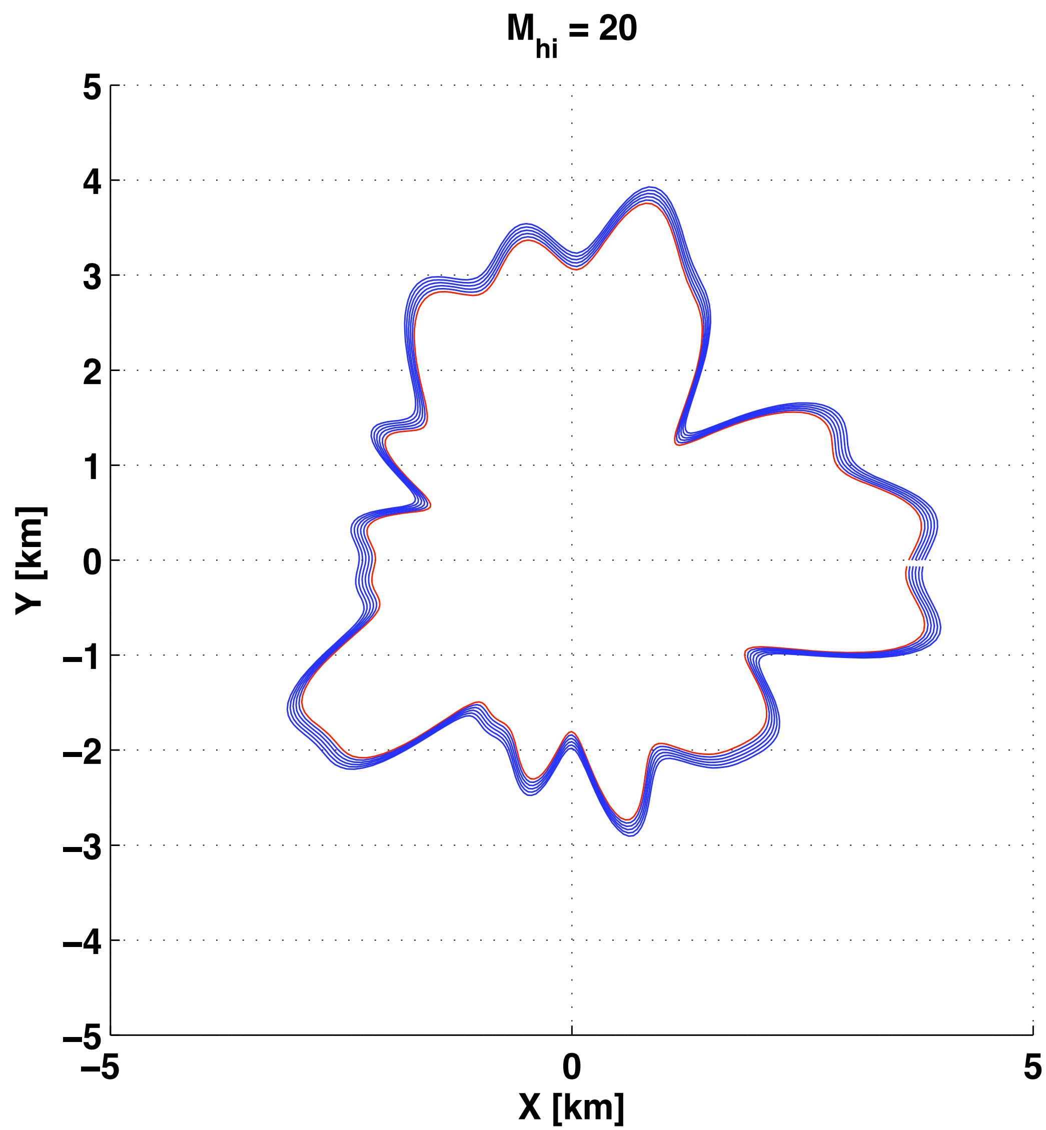
- R = 5 km
- M = 1, 2, ..., 8, ... (black)



Simulated Plumes

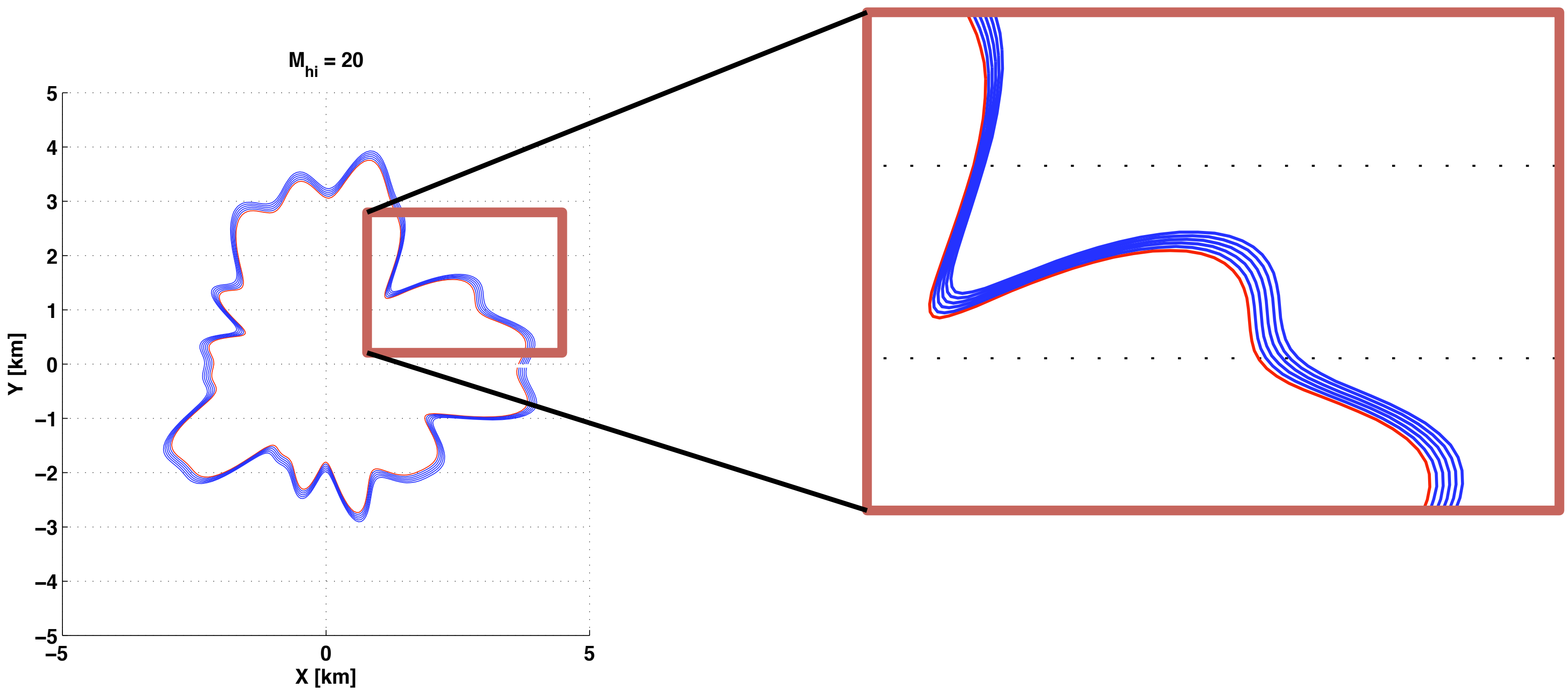
'Actual' plume:

- R = 5 km
- Max # of Fourier modes, $M_{hi} = 20$



Time Variation

- Increase the amplitude of each Fourier order linearly in time to simulate plume spreading (from diffusion/turbulence)



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Introduce AUVs

- AUVs sample points on the original plume boundary
- Evenly space the AUVs about the plume origin, on the boundary, with navigation error of
  - $\pm 10°$ in azimuthal position
  - $\pm$ 500 m in radial position

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Estimating the Plume from AUV Samples

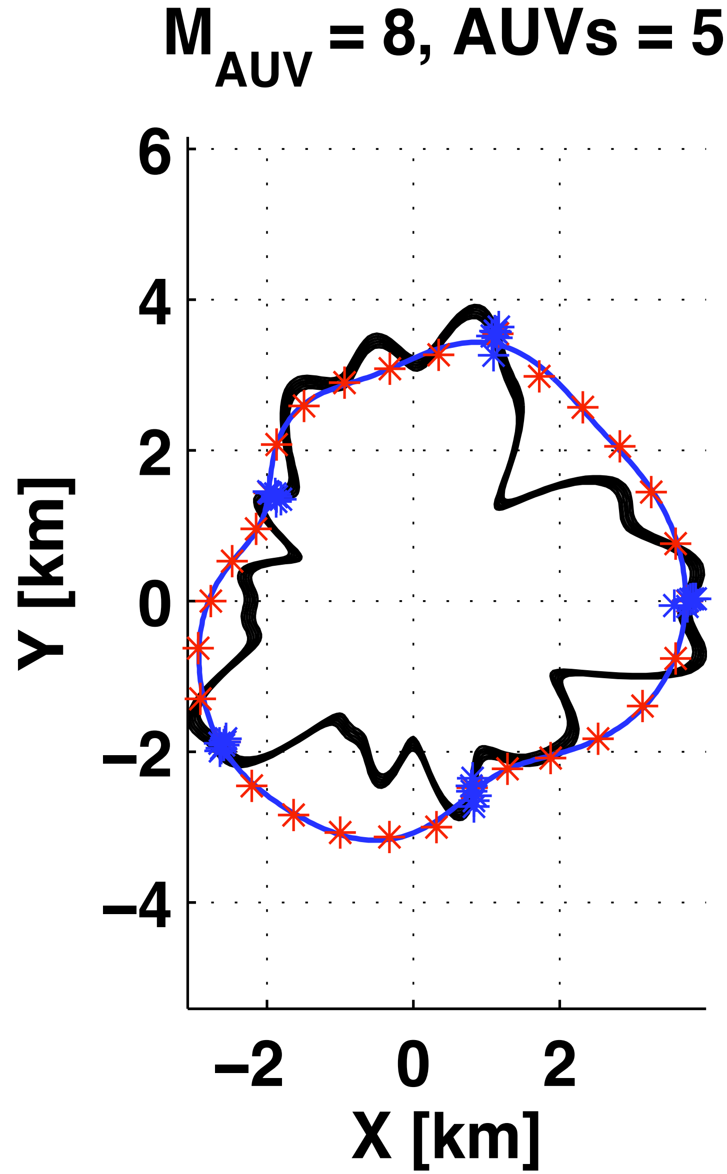
- Say, AUVs sample the moving plume edge every 2 minutes, and
- the plume is moving slowly enough that all samples in the last 10 minutes will give a decent estimate of the average plume boundary.

Estimating the Plume from AUV Samples

[blue stars]

- If we have 5 AUVs in the water,
- this gives us 30 samples total (at 0, 2, 4, …, 10 min).
- Thus, we can solve for up to 14 Fourier orders!

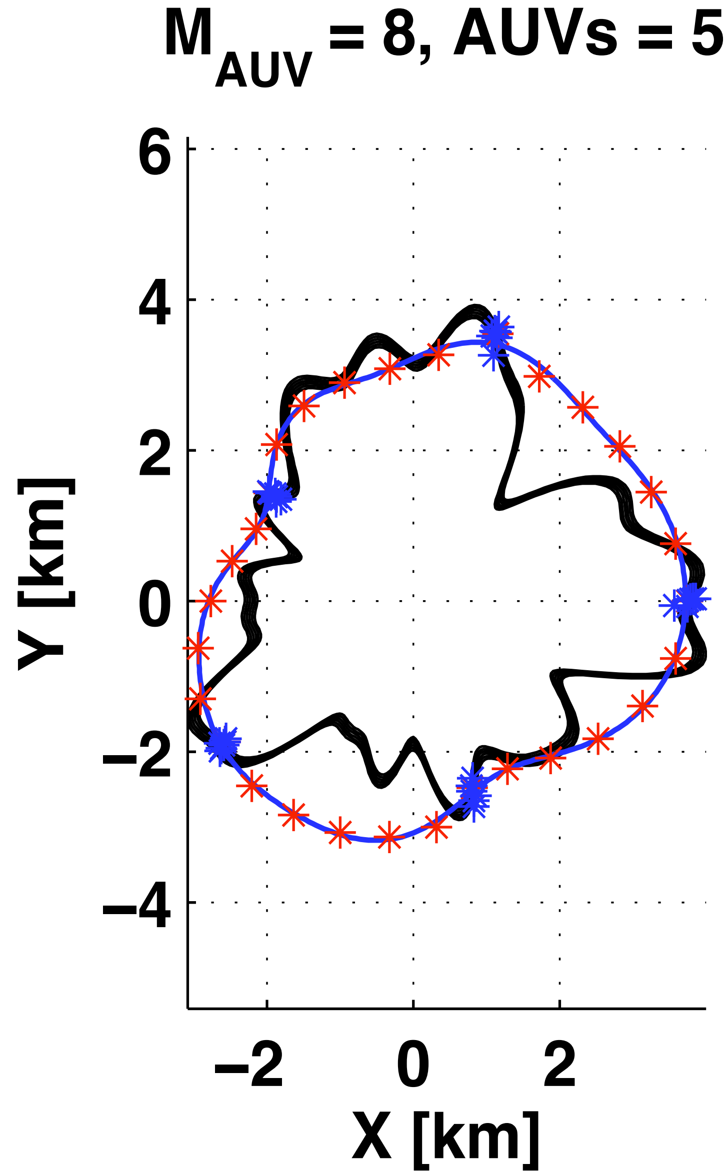
$M \leq \text{floor}\{(N_{samples}-1)/2\}$



Estimating the Plume from AUV Samples

[red stars]

- Interpolate these samples to 30 evenly-spaced points about the plume (I use a cubic interpolation, but there are probably more robust methods out there).



Estimating the Plume from AUV Samples

- Back out estimates of the 'actual' plume coefficients (A_m & ϕ_m) using Fourier analysis on the (N_{AUV} = 30) interpolated AUV positions:

$$\Phi_{avg} \approx R \tag{2}$$

$$A_{AUV,m=0} = \frac{1}{2} * \frac{|fft(\Phi_{AUV,m=0}|\theta_{AUV})|}{N_{AUV}/2} - \Phi_{avg} \tag{3}$$

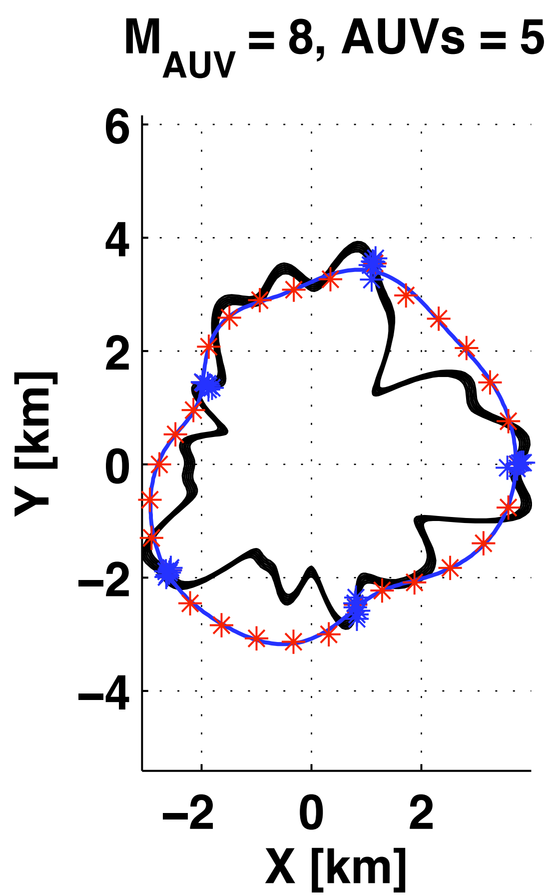
$$A_{AUV,m=1:M} = \frac{|fft(\Phi_{AUV,m=1:M}|\theta_{AUV})|}{N_{AUV}/2} \tag{4}$$

$$\phi_{AUV,m=0:M} = angle[fft(\Phi_{AUV,m=0:M}|\theta_{AUV})] \tag{5}$$

Estimating the Plume from AUV Samples

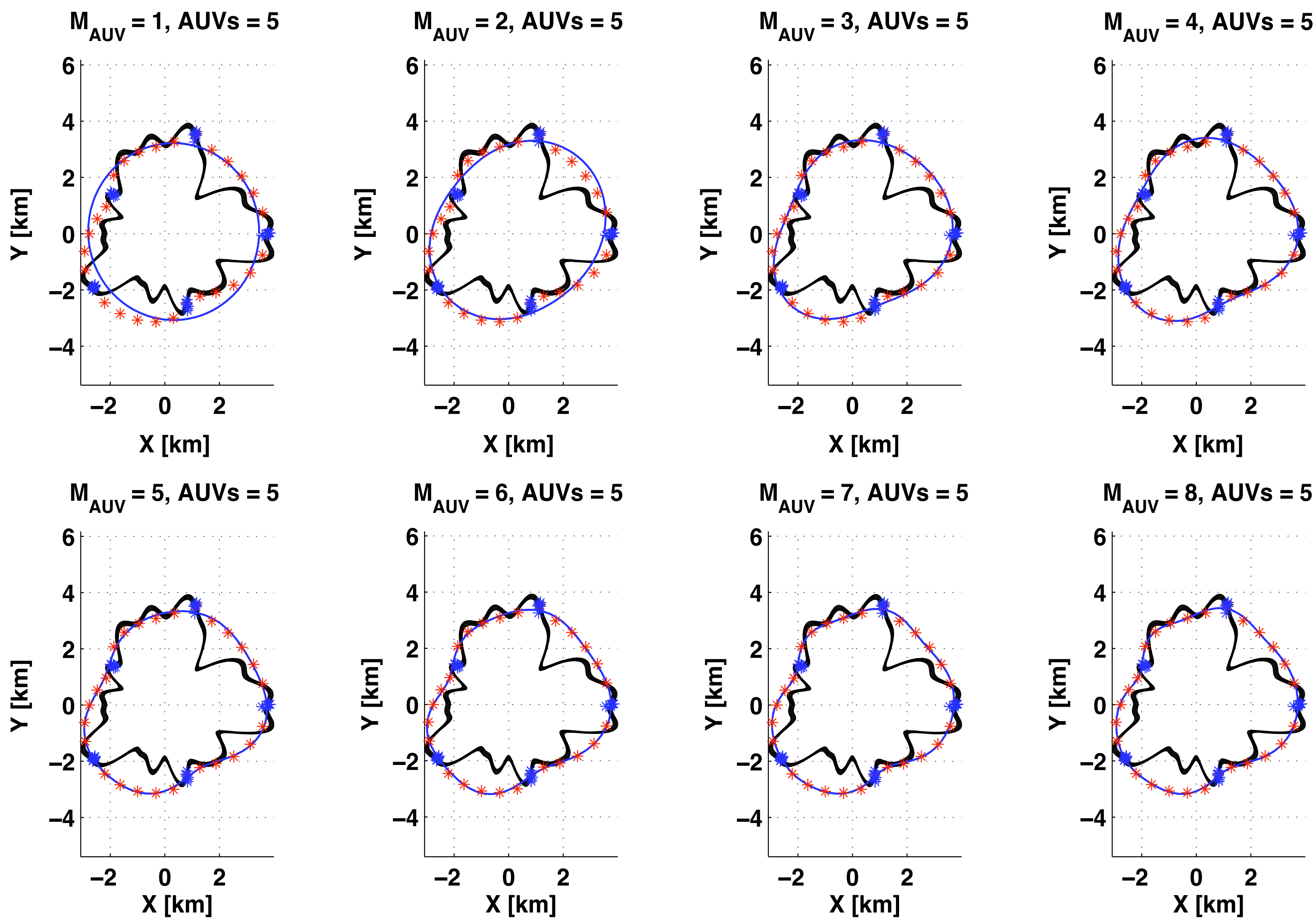
- Reconstruct the plume [blue line]:

$$\Phi_{AUV,M} = \Sigma_{m=0}^{M} [A_{AUV,m} * cos(m\theta_{AUV} + \phi_{AUV,m})] + \Phi_{avg}. \quad (6)$$



Estimating the Plume from AUV Samples

- M_{AUV} = 1, 2, …, 8 [blue line]



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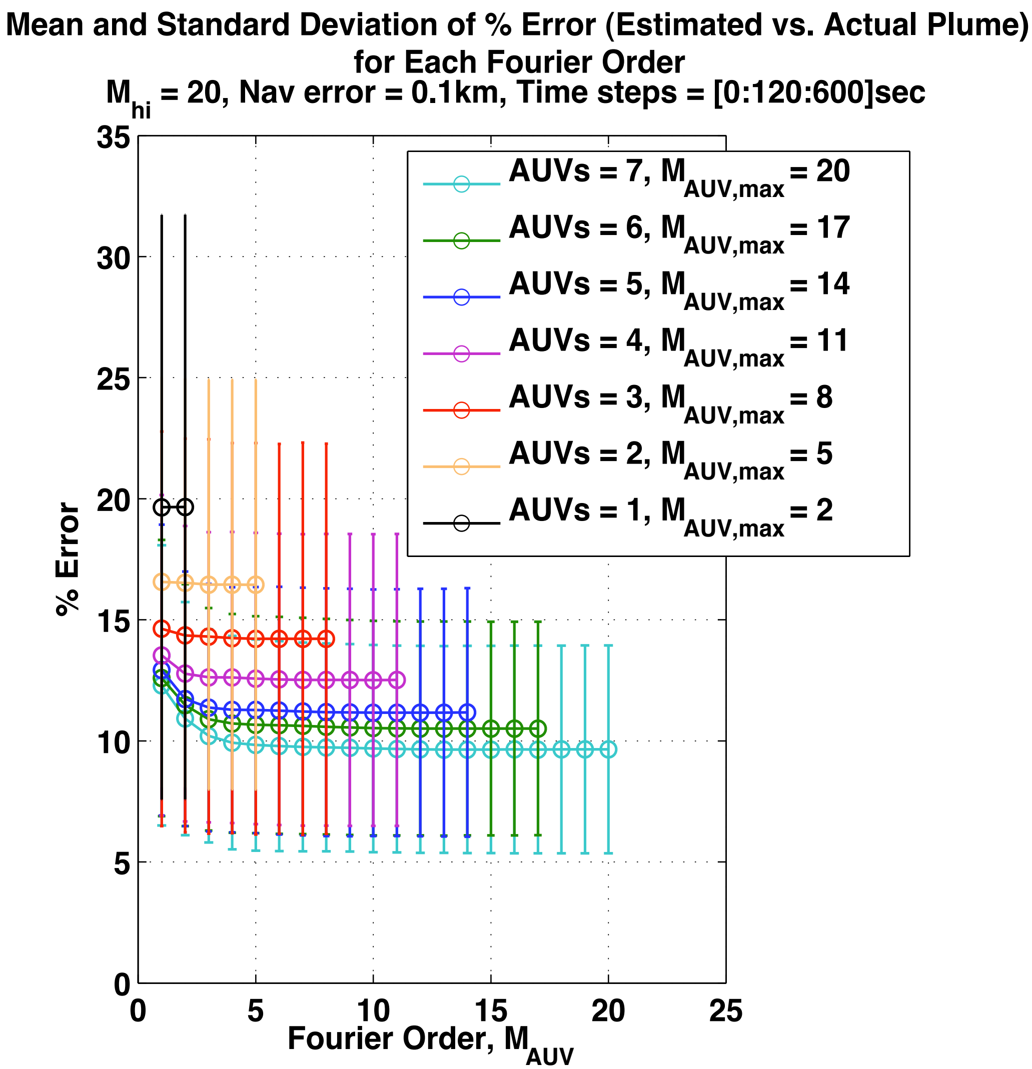
Evaluate Errors

$$\%Error_{plume} = \frac{|\Phi_{estimated} - \Phi_{actual,time-avg}|}{\Phi_{actual,time-avg}}. \quad (7)$$



- For the 'actual' plume shape, $\Phi_{actual,\ time\text{-}avg}$, we estimate a plume shape of order M_{AUV}, $\Phi_{estimated}$, using the AUV data.

Future Additions

- Plume prediction by temporal extrapolation of plume shape based on
  - Diffusion & turbulence
  - Currents
- Improve the AUV position interpolation scheme
- Link to ocean models for background environment
- Incorporate into MOOS & IvP Helm for autonomous plume tracking

Thanks!

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