Seamark-assisted Navigation

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Motivation

Navigation requires the ability of a vehicle to determine its position and speed

Navigation is an active field in underwater mobile networks, typical solutions include

- Inertial navigation based approaches
  - Has accumulated error
- GPS-assisted inertial navigation
  - Requires periodical surfacing
  - Could lose track of target
  - Could be exposed to enemies
- Image processing based approaches
  - Require vehicles to be close to known marks

Our objectives

- Provide accurate location information
- Navigation without surfacing requirement
- Simple enough to be practical

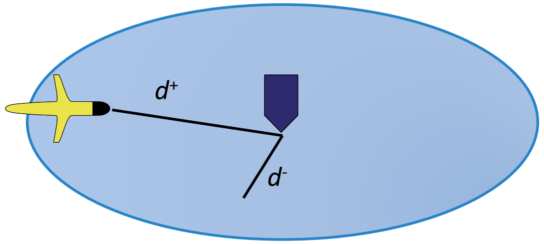
Main Idea

Essentially assisted inertial navigation

- Inertial navigation information is corrected with seamarks

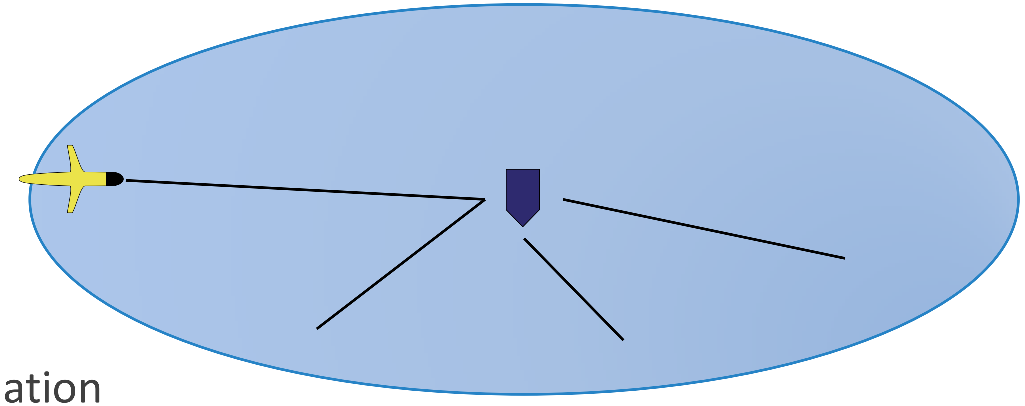
Seamarks are lightweight undersea node

- Responsible for ONE geographical area
- Help AUVs measure round trip distance d(=d^{+}+d^{-})

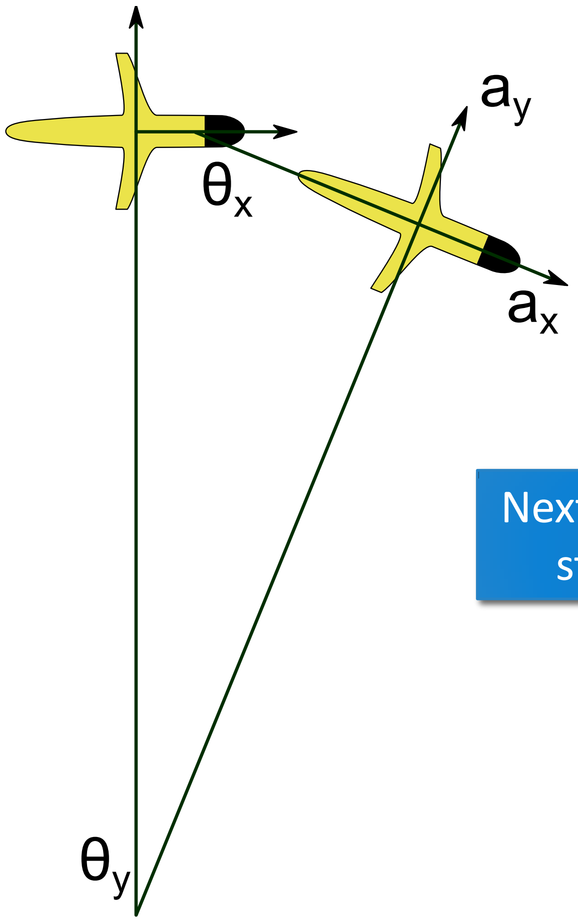


Main Idea

- AUV assumes first contact with seamark is at $(0,0,0)$
- AUV uses multiple measurement to determine seamark in this coordinate system
- Seamark global position is known
- → AUV global position is obtained with coordinate translation



Technical Details



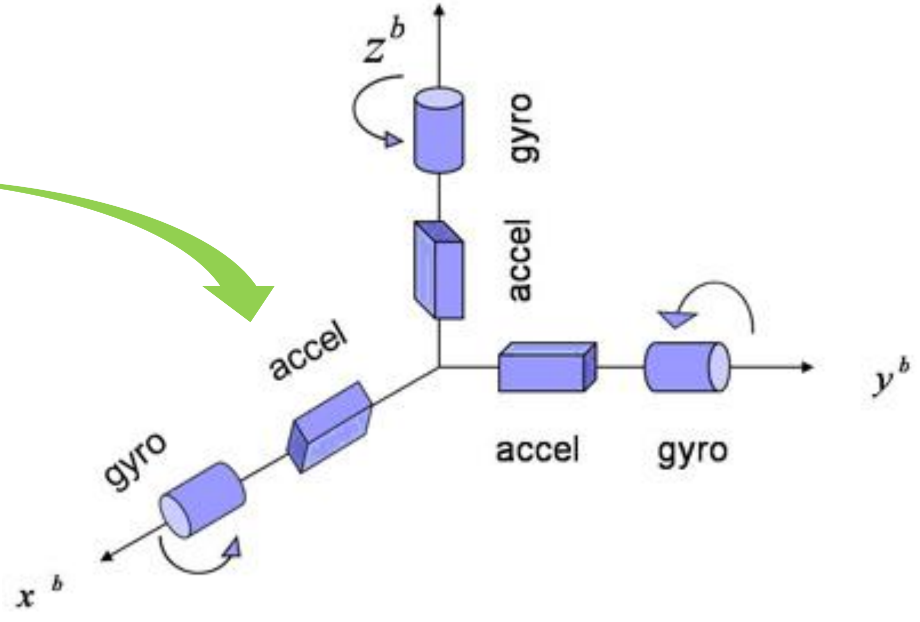
Initial information:
p_0, v_0

IMU measurements:
$\theta(t), a(t)$ -> $v(t), p(t)$

Next time step

Correcting velocity information

Correcting position information



Inertial Measurement Unit
3 accelerometers, 3 gyroscopes

Correcting Position Information

Input:

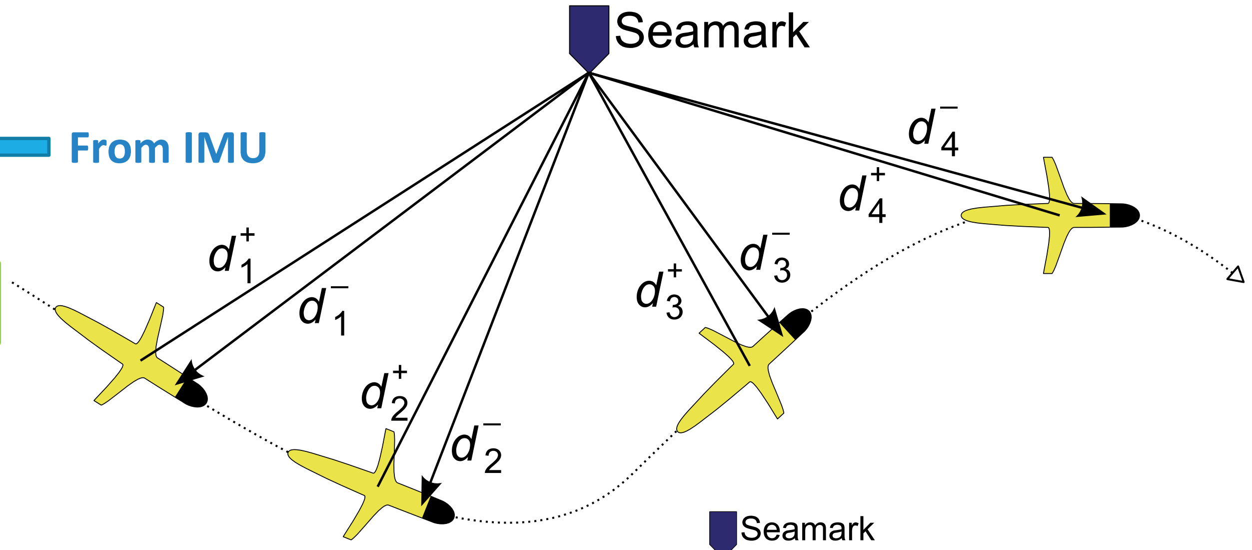
- Start measurement points $\{p_i^b\}_{i=1}^n$
- End measurement points $\{p_i^e\}_{i=1}^n$
- Noisy measurements:

From IMU

$$d_i = d_i^+ + d_i^- + \omega_i$$

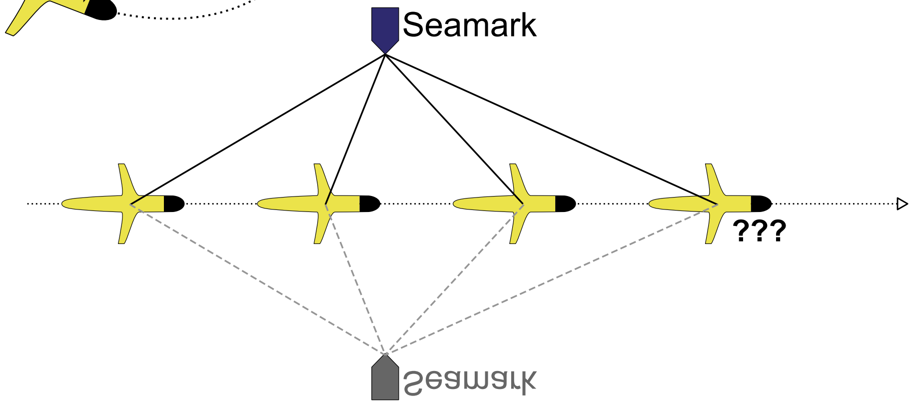
Output: p_b (Seamark position)

From AComm



Iterated least square estimation

$$\hat{\mathbf{p}}^b_{(k+1)} = \hat{\mathbf{p}}^b_{(k)} + \left(\mathbf{J}'^H_{(k)}\mathbf{R}^{-1}\mathbf{J}^H_{(k)}\right)^{-1}\mathbf{J}^H_{(k)}\mathbf{R}^{-1}\left(\mathbf{d} - \mathbf{h}(\hat{\mathbf{p}}^b_{(k)})\right)$$



Correcting Position Information II

Input:

- Start measurement points $\{p_i^b\}_{i=1}^n$
- End measurement points $\{p_i^e\}_{i=1}^n$
- Noisy measurements:

$$d_i = d_i^+ + d_i^- + \omega_i$$

Output: p_b (Seamark position)

$$\underbrace{\begin{bmatrix} d_1 \\ d_2 \\ \vdots \\ d_n \end{bmatrix}}_{=:\mathbf{d}} = \underbrace{\begin{bmatrix} h(\mathbf{p}^b, \mathbf{p}_1^s, \mathbf{p}_1^e) \\ h(\mathbf{p}^b, \mathbf{p}_2^s, \mathbf{p}_2^e) \\ \vdots \\ h(\mathbf{p}^b, \mathbf{p}_n^s, \mathbf{p}_n^e) \end{bmatrix}}_{=:\mathbf{h}(\mathbf{p}^b)} + \underbrace{\begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix}}_{=:\boldsymbol{\omega}}$$

$$h(\mathbf{p}^b, \mathbf{p}_i^s, \mathbf{p}_i^e) = \|\mathbf{p}^b - \mathbf{p}_i^s\| + \|\mathbf{p}^b - \mathbf{p}_i^e\|$$

Iterated least square estimation

$$\hat{\mathbf{p}}_{(k+1)}^b = \hat{\mathbf{p}}_{(k)}^b + \left(\mathbf{J}'^H_{(k)}\mathbf{R}^{-1}\mathbf{J}_{(k)}^H\right)^{-1}\mathbf{J}_{(k)}^H\mathbf{R}^{-1}\left(\mathbf{d} - \mathbf{h}(\hat{\mathbf{p}}_{(k)}^b)\right)$$

$$\mathbf{J}_{(k)}^H = \begin{bmatrix} \left(\frac{\mathbf{p}^b - \mathbf{p}_1^s}{\|\mathbf{p}^b - \mathbf{p}_1^s\|} + \frac{\mathbf{p}^b - \mathbf{p}_1^e}{\|\mathbf{p}^b - \mathbf{p}_1^e\|}\right)' \\ \left(\frac{\mathbf{p}^b - \mathbf{p}_2^s}{\|\mathbf{p}^b - \mathbf{p}_2^s\|} + \frac{\mathbf{p}^b - \mathbf{p}_2^e}{\|\mathbf{p}^b - \mathbf{p}_2^e\|}\right)' \\ \vdots \\ \left(\frac{\mathbf{p}^b - \mathbf{p}_m^s}{\|\mathbf{p}^b - \mathbf{p}_m^s\|} + \frac{\mathbf{p}^b - \mathbf{p}_m^e}{\|\mathbf{p}^b - \mathbf{p}_m^e\|}\right)' \end{bmatrix}$$

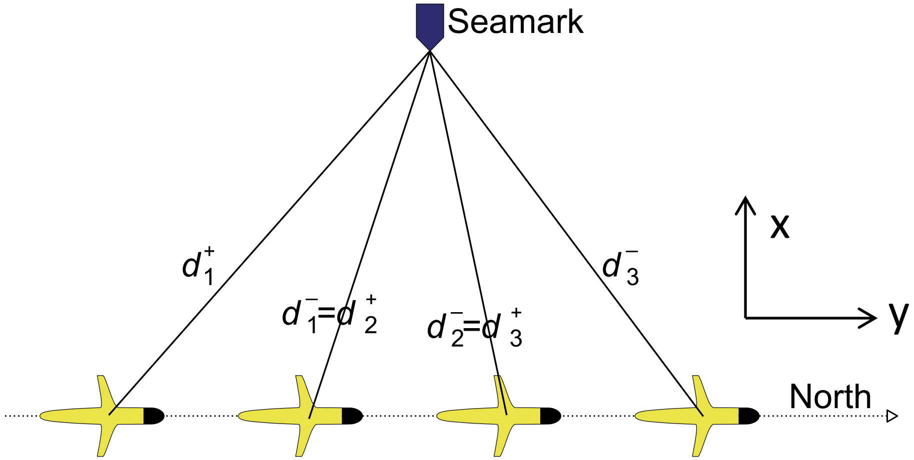
Correcting Velocity Information

Input:

- Initial position p_0;
- Constant velocity, linear trajectory
- Noisy measurements:

$$d_i = d_i^+ + d_i^- + \omega_i$$

Output: vehicle speed



Correcting Velocity Information II

Input:

- Initial position p_0;
- Constant velocity, linear trajectory
- Noisy measurements:

$$d_i = d_i^+ + d_i^- + \omega_i$$

From AComm

Output: vehicle speed

$$\underbrace{\begin{bmatrix} d_1 \\ d_2 \\ \vdots \\ d_n \end{bmatrix}}_{=:\mathbf{d}(\mathbf{u})} = \underbrace{\begin{bmatrix} g_1 \\ g_2 \\ \vdots \\ g_n \end{bmatrix}}_{=:\mathbf{g}(\mathbf{u})} + \underbrace{\begin{bmatrix} \omega_1 \\ \omega_2 \\ \vdots \\ \omega_n \end{bmatrix}}_{=:\boldsymbol{\omega}}$$

Iterated least square estimation

$$\mathbf{u} = \begin{bmatrix} x_0 & y_0 & v \end{bmatrix}'$$

$$\mathbf{u}_{(k+1)} = \mathbf{u}_{(k)} + \left(\mathbf{J}'^{G}_{(k)}\mathbf{R}^{-1}\mathbf{J}^{G}_{(k)}\right)^{-1} \mathbf{J}^{G}_{(k)}\mathbf{R}^{-1}\left(\mathbf{d} - \mathbf{g}(\mathbf{u}_k)\right)$$

$$\mathbf{J}^G(\mathbf{e}) = \begin{bmatrix} \frac{x_0 - x^p}{g_1^{(1)}} & \frac{y_0 - y^p}{g_1^{(1)}} & 0 \\ \frac{x_0 - x^p}{g_2^{(1)}} & \frac{y_0 - y^p + vt_1}{g_2^{(1)}} & \frac{y_0 - y^p + vt_1}{g_2^{(1)}} t_1 \\ \vdots & \vdots & \vdots \\ \frac{x_0 - x^p}{g_n^{(1)}} & \frac{y_0 - y^p + v\sum_{i=1}^{n-1} t_i}{g_n^{(1)}} & \frac{y_0 - y^p + v\sum_{i=1}^{n-1} t_i}{g_n^{(1)}} \sum_{i=1}^{n-1} t_i \end{bmatrix} + \begin{bmatrix} \frac{x_0 - x^p}{g_1^{(2)}} & \frac{y_0 - y^p + vt_1}{g_1^{(2)}} & \frac{y_0 - y^p + vt_1}{g_1^{(2)}} t_1 \\ \frac{x_0 - x^p}{g_2^{(2)}} & \frac{y_0 - y^p + v(t_1 + t_2)}{g_2^{(2)}} & \frac{y_0 + y_p + v(t_1 + t_2)}{g_2^{(2)}} (t_1 + t_2) \\ \vdots & \vdots & \vdots \\ \frac{x_0 - x^p}{g_n^{(2)}} & \frac{y_0 - y^p + v\sum_{i=1}^{n} t_i}{g_n^{(2)}} & \frac{y_0 - y^p + v\sum_{i=1}^{n} t_i}{g_n^{(2)}} \sum_{i=1}^{n} t_i \end{bmatrix}$$

Round trip based on IMU measurements

$$g_k = \underbrace{\sqrt{(x_0 - x^p)^2 + \left(y_0 - y^p + v\sum_{i=1}^{k-1} t_i\right)^2 + (z_0 - z^p)^2}}_{=:g_k^{(1)}} + \underbrace{\sqrt{(x_0 - x^p)^2 + \left(y_0 - y^p + v\sum_{i=1}^{k} t_i\right)^2 + (z_0 - z^p)^2}}_{=:g_k^{(2)}}$$

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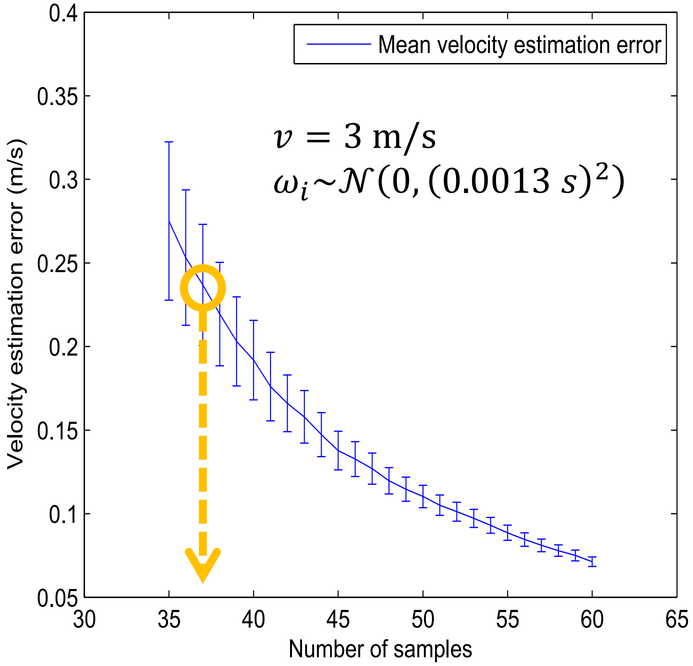
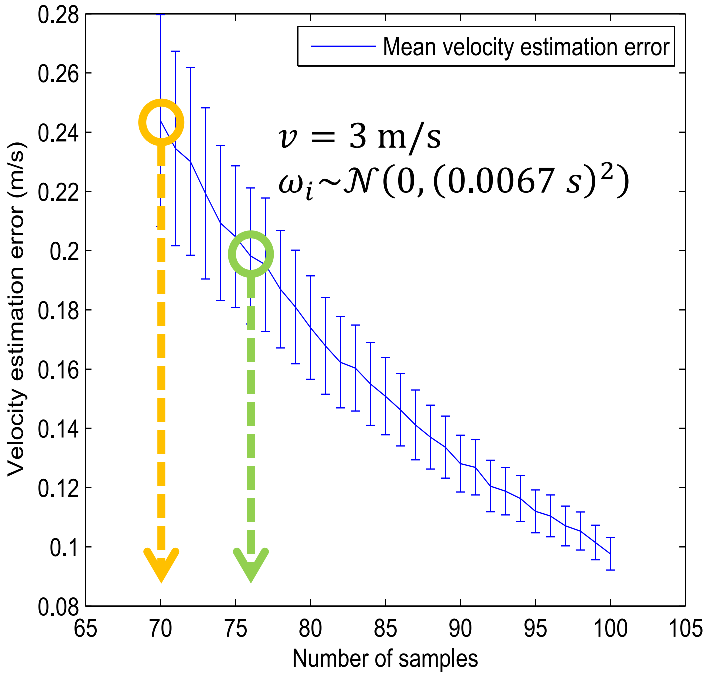
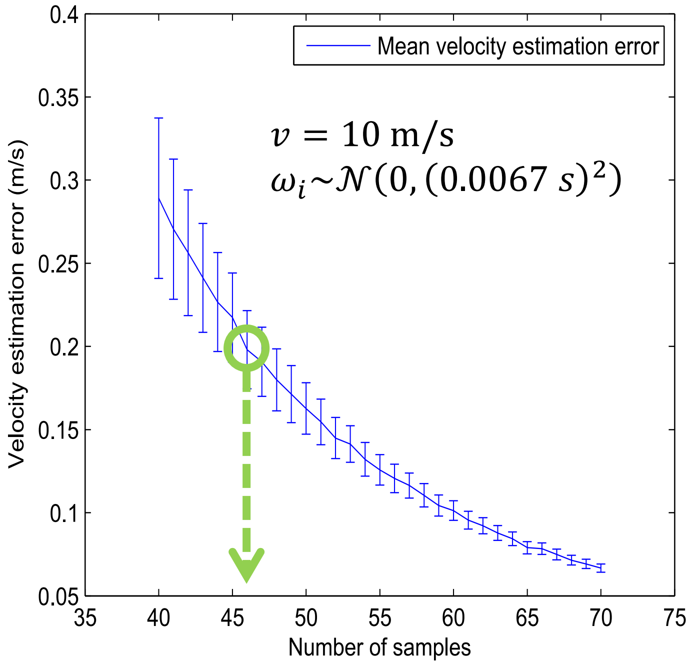
Simulation Results for Velocity Correction







More noise → more samples, to get the same level of accuracy

Our scheme can work well with fast moving AUVs. But it won't work for standing objects

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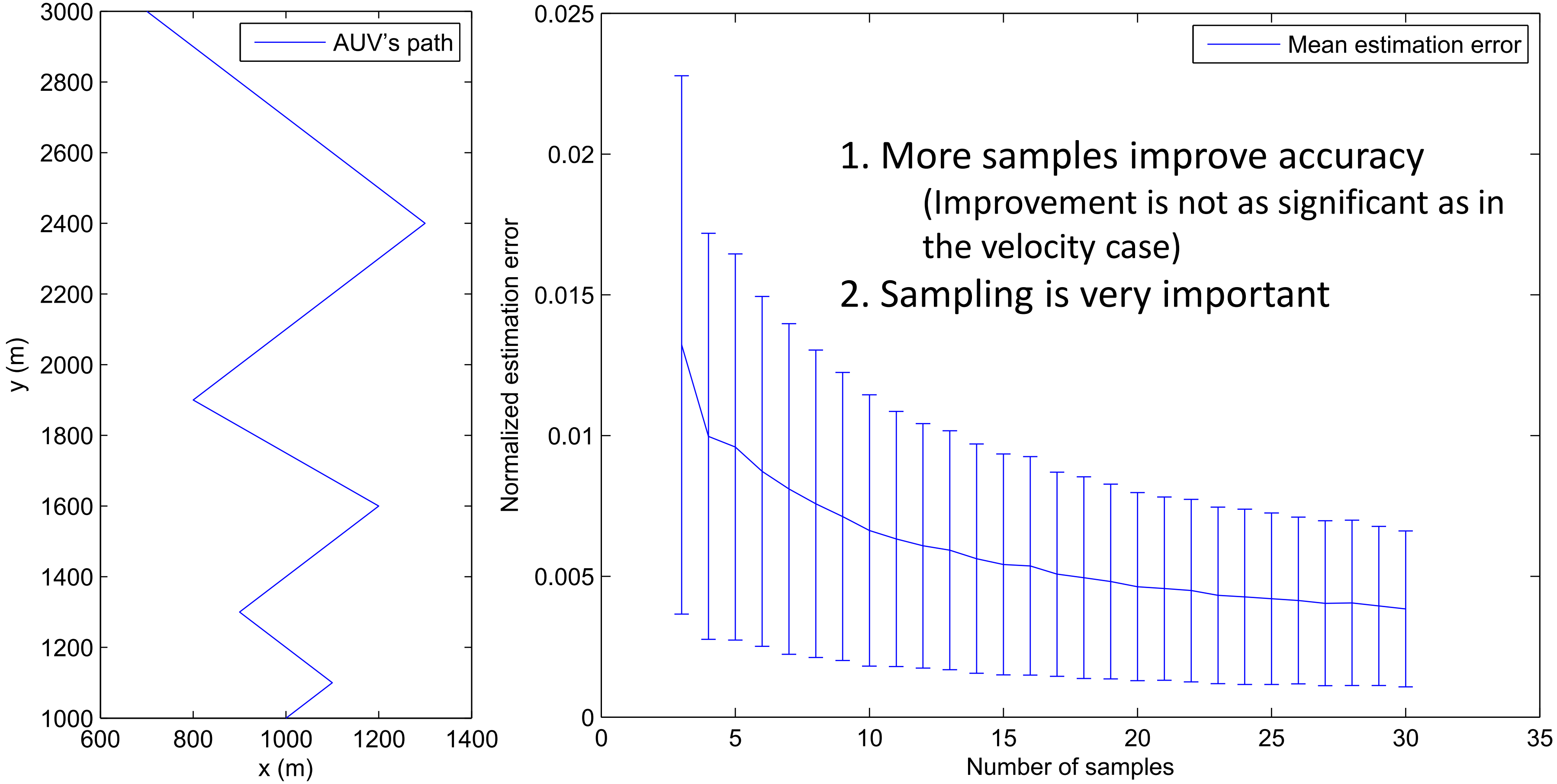
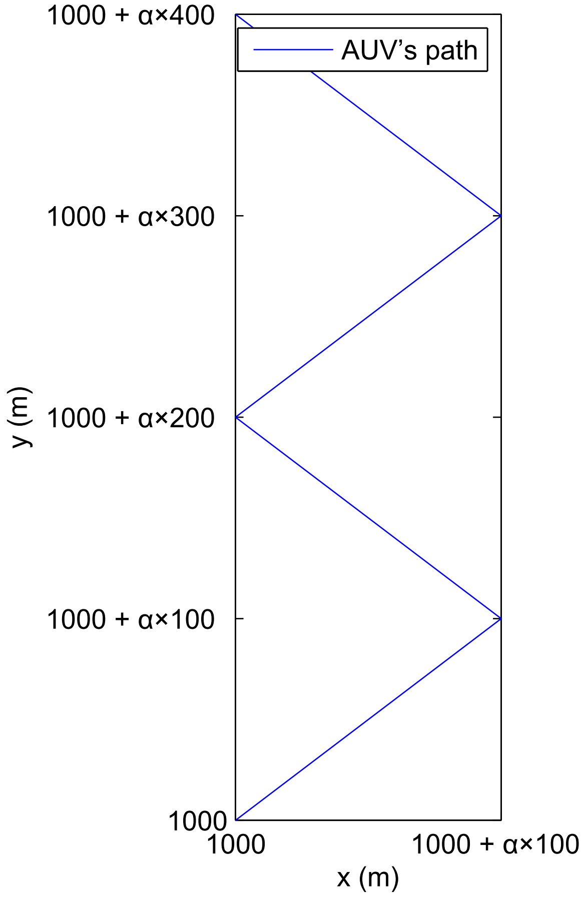
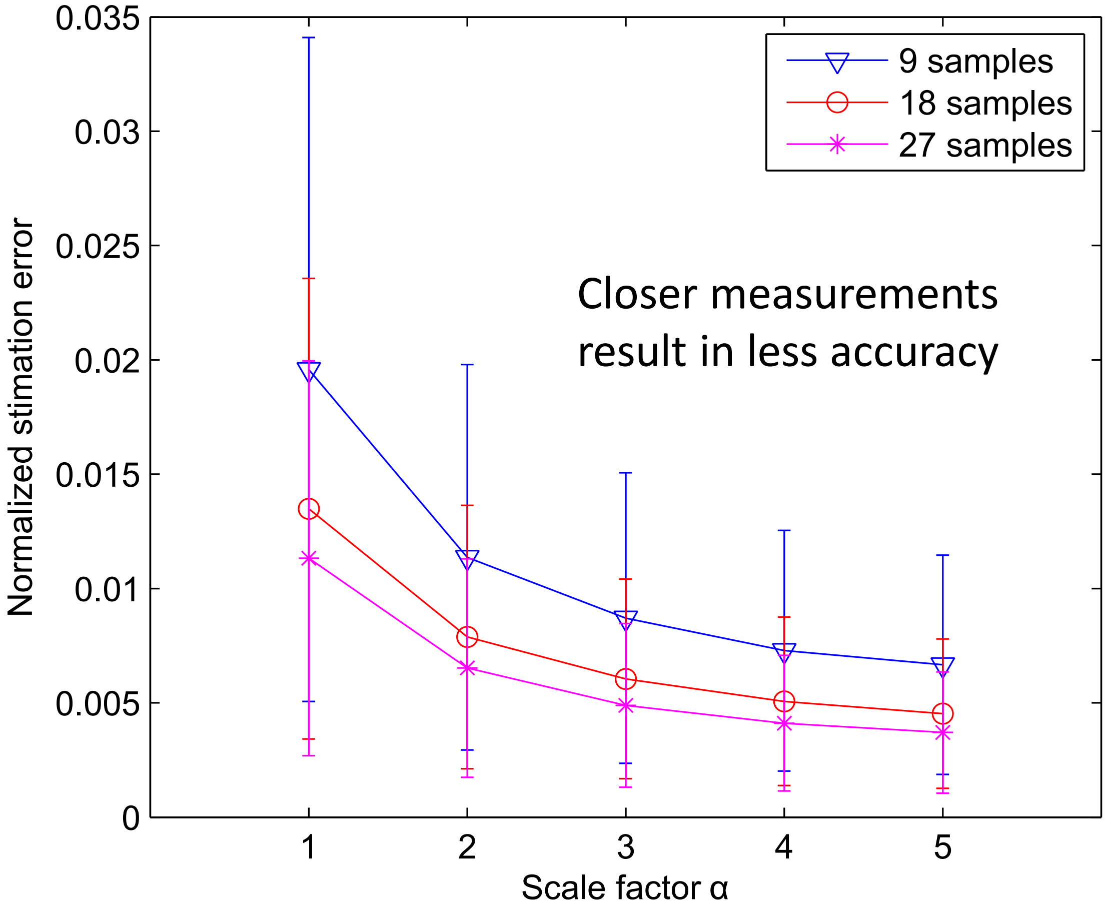
Simulation Results for Position Correction



1. More samples improve accuracy
   (Improvement is not as significant as in the velocity case)
2. Sampling is very important

Effects of Distance Between Samples





Summary

Propose and simulate an INS assisted navigation scheme

- Uses commonly available sensors
- Practical to implement
- Suitable for applications that require no surfacing

Simulations show promising results

Future work

- Implement our scheme on real devices
- Investigate time synchronization with the help of seamarks
- Study if Doppler measurements could improve better accuracy
- Explore how to deal with some noises, such as ocean current