Overview of Synthetic Aperture Sonar Technology

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Synthetic Aperture Sonar

We'll be discussing US Navy SAS systems:

- Two classes:
  - High-frequency, high-resolution (1" x 1")
  - Low-frequency broadband (subsurface imaging)
- Carried by autonomous underwater vehicles (AUVs)
- Image reconstruction hindered by unwanted vehicle motion

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Synthetic Aperture Sonars

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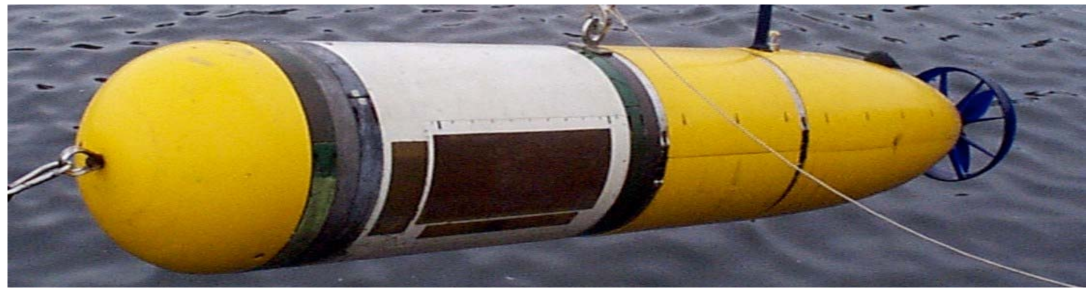

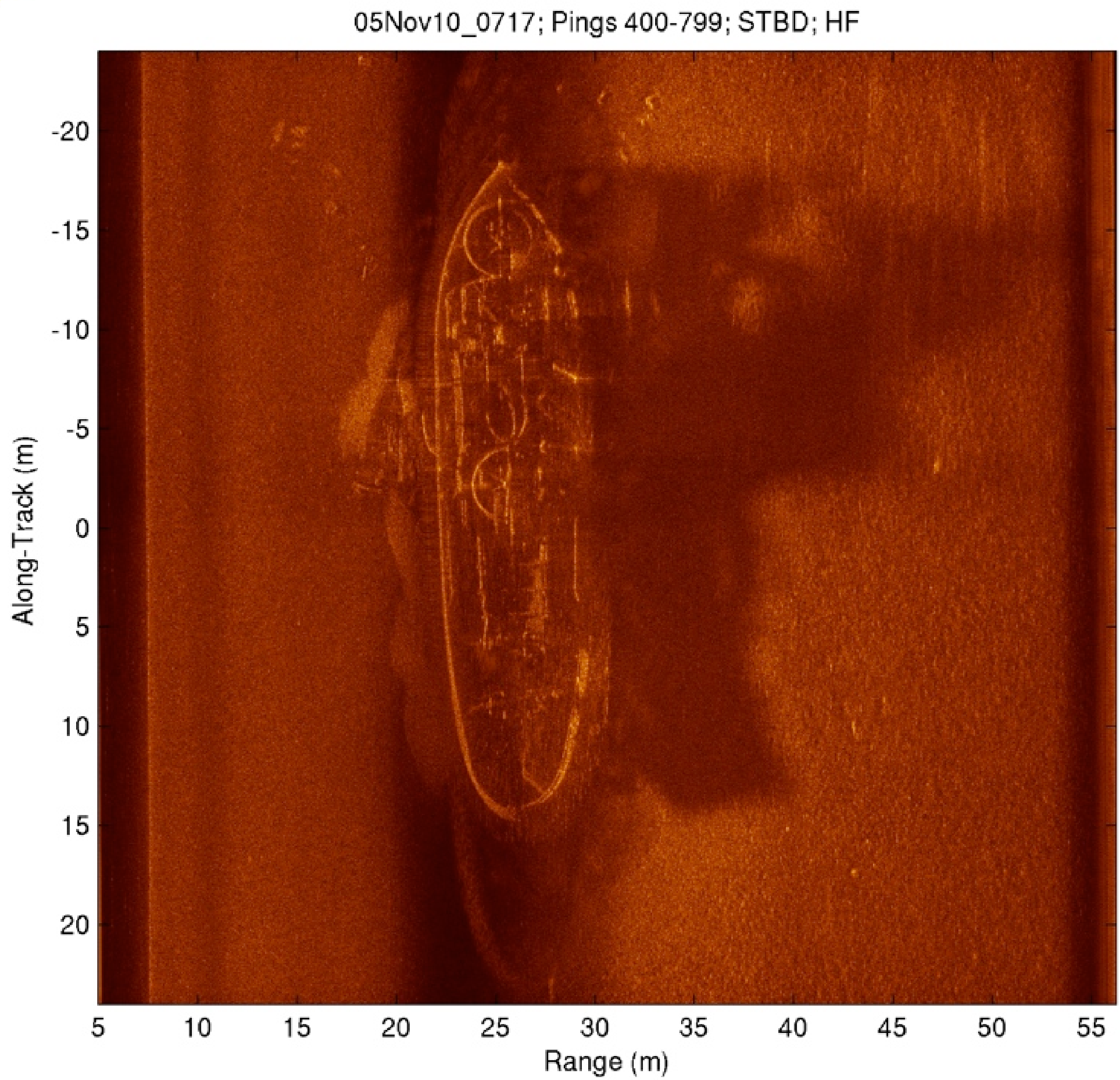
05Nov10_0717; Pings 400-799; STBD; HF
Along-Track (m)
-20
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Range (m)
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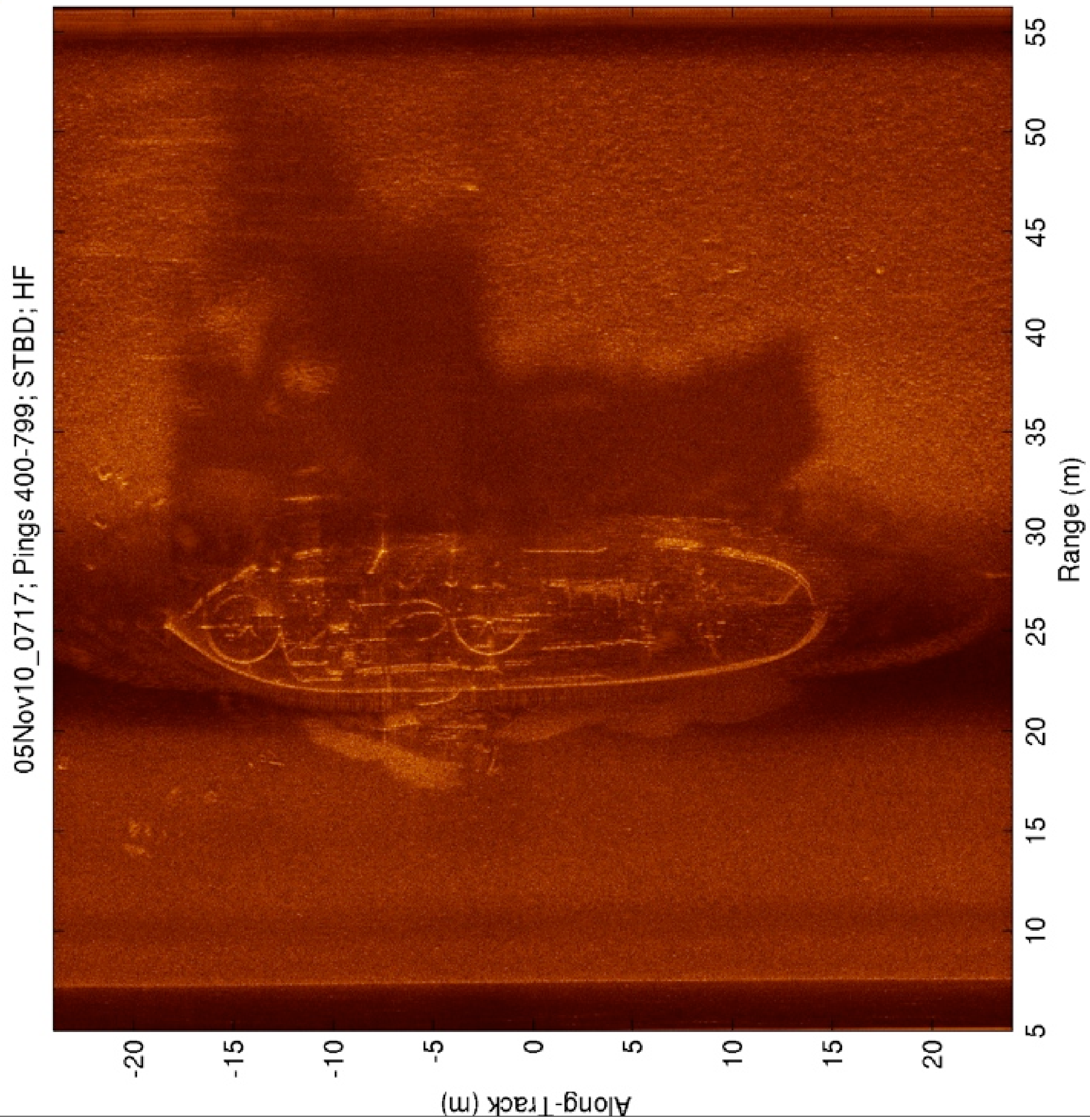

05Nov10_0717; Pings 400-799; STBD; HF
Range (m)
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-20
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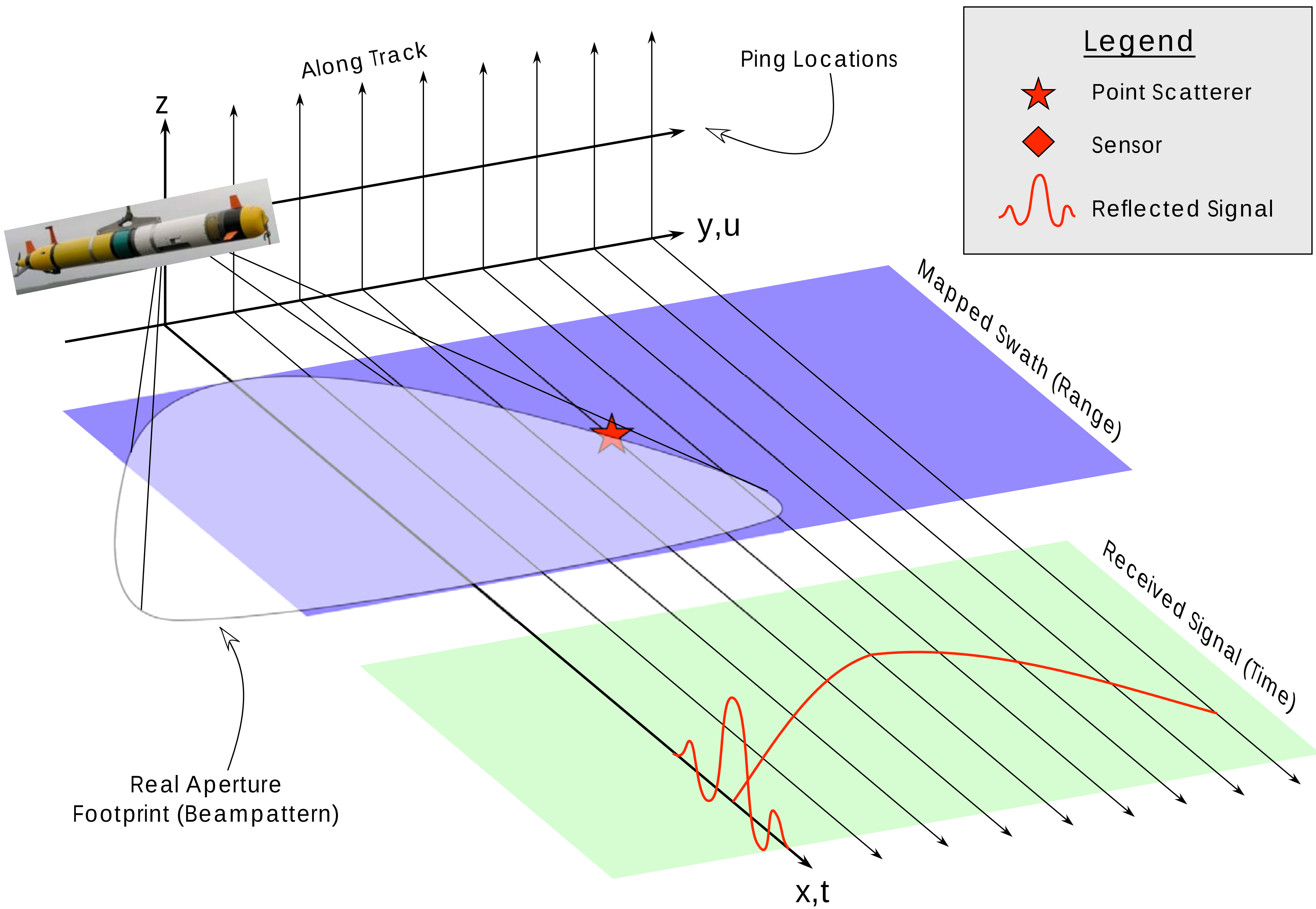
SAS Image Reconstruction

What goes into making a SAS image?

- Multiple "pings" (transmit and receive steps) are combined to reconstruct (or, focus) the image.
- Consider any point on the sea floor. It is 'seen' by many pings as the sonar passes by.
- All the returns from a single point are processed coherently to produce an estimate of the reflectivity of the point.
    - Like a 2d spatial matched filter: we know what the return signal phase history should be.

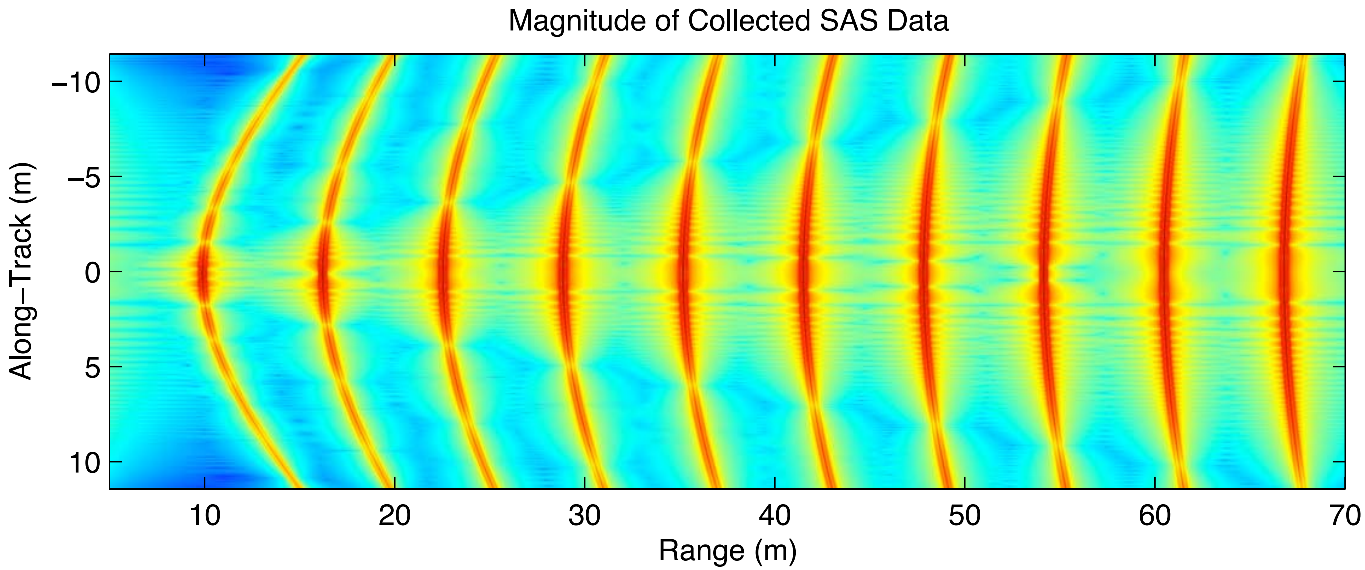
SAS Operation

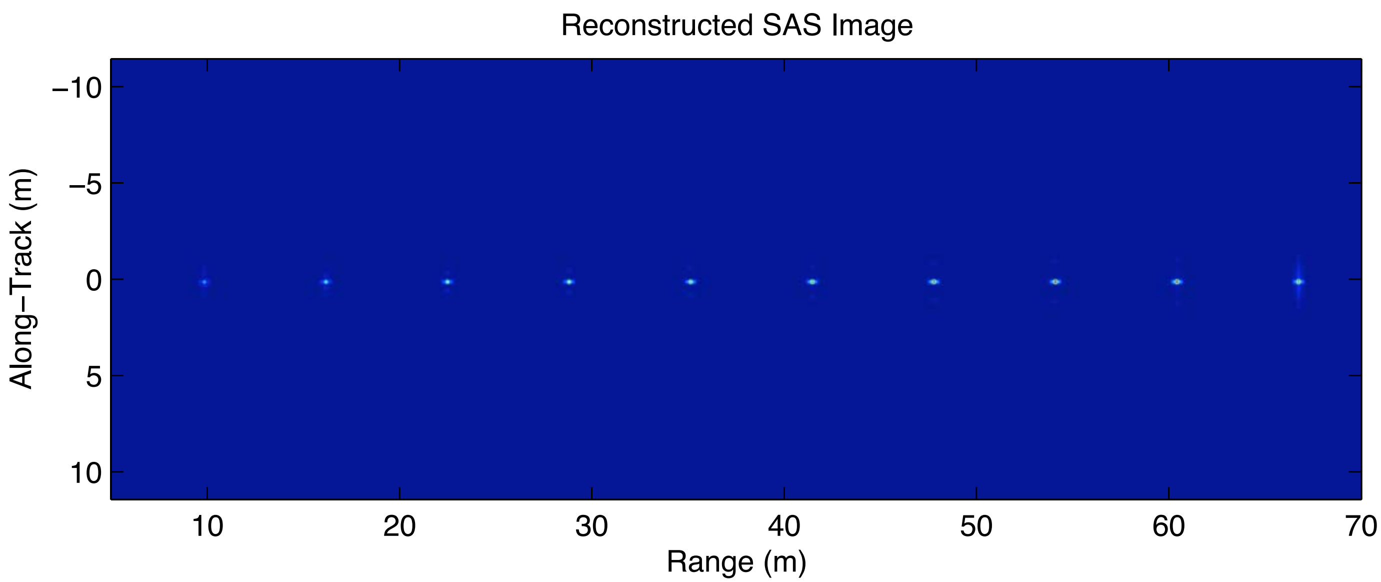


SAS Operation

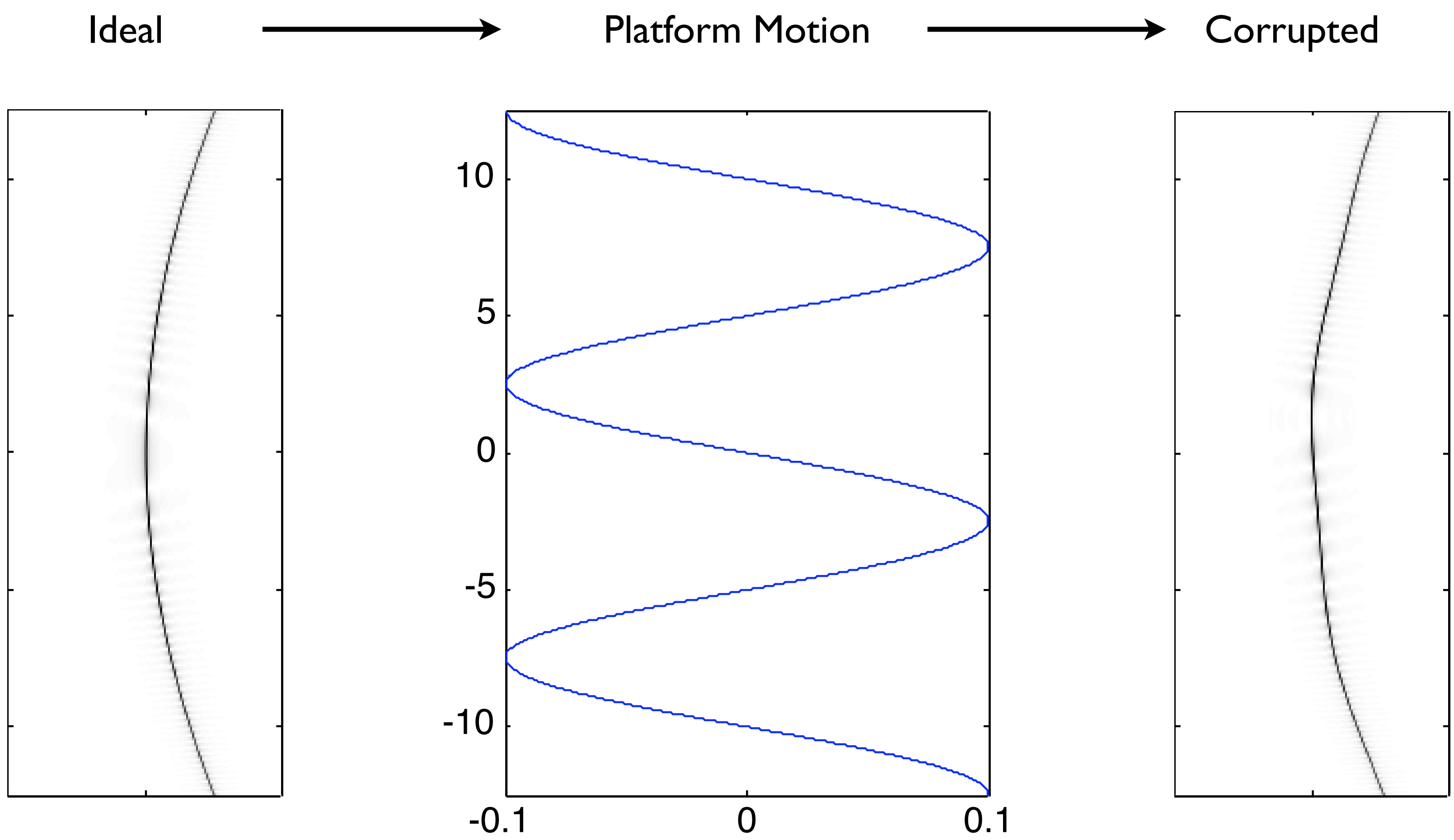
Go to Quicktime movie.
(Pattered after CSIP SAR Animation)

SAS Overview





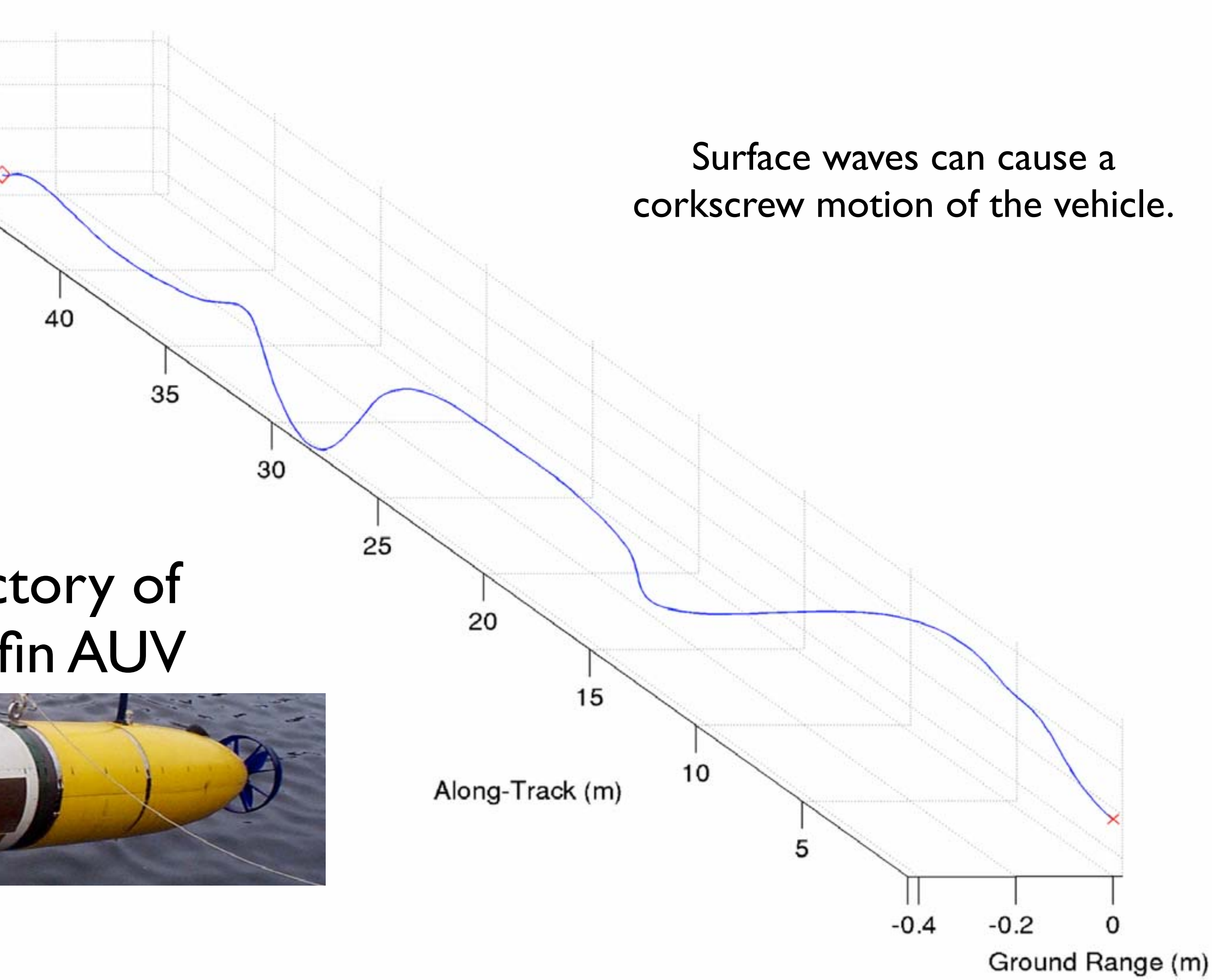
Platform Motion



Platform Motion

- One synthetic aperture = $R\theta = R\lambda/D$. (R = range, θ = 3dB beamwidth, and D = sensor width.)
- The rule of thumb requirement for perfect reconstruction is for the array to deviate less than $\lambda/8$ over a single synthetic aperture.
- This almost never happens in the real world, so we turn to motion estimation and compensation.
- Note that the SA length grows with range, making good focus harder to achieve at long ranges.
- At 50m range, the SA lengths for SSAM are:
  - $D = 0.0508$ m; $f = 40$ kHz; $\lambda = 0.0375$ m; LSA = 37 m
  - $D = 0.0508$ m; $f = 120$ kHz; $\lambda = 0.0125$ m; LSA = 12 m

Platform Motion



Surface waves can cause a corkscrew motion of the vehicle.

3d trajectory of 21" Bluefin AUV

Motion Estimation and Compensation

- High-end AUVs are typically equipped with inertial navigation systems for use while submerged. In general, these are not adequate for the needs of SAS motion estimation/compensation.

- INS units are costly. We'd like to be able to get good results using cheaper sensors.

- SAS motion estimation is done by overlapping a part of the receiver array from one ping to the next. In other words, the location of the first few channels of Ping *N*-1 are (approximately) in the same place as the last few channel of Ping *N*.

- The returns from the overlapping channels should be very nearly the same except for a time delay.

Motion Estimation and Compensation

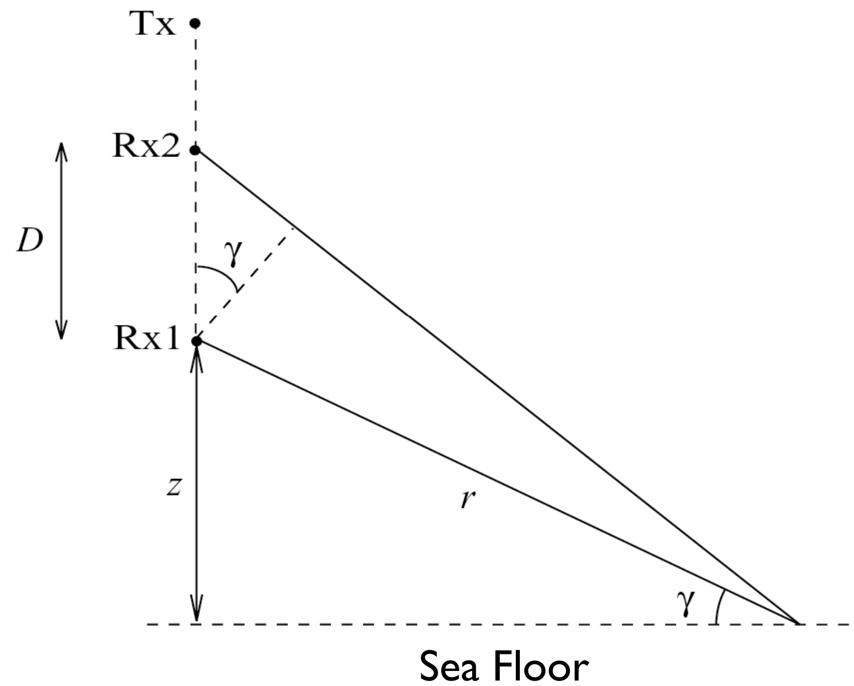
- The measured time delay is a function of the motion, but it is not in general proportional to the ping-to-ping displacement of the sensor.
- The challenge of motion estimation is to properly decompose the time delay into the components of the motion.
- We measure the time delays and use them with a model to solve for the vehicle motion.
- We'll describe two solutions, but first we'll look at time delay estimation in detail.

Time Delay Estimation

Motion estimation and interferometry are two sides of the same coin.

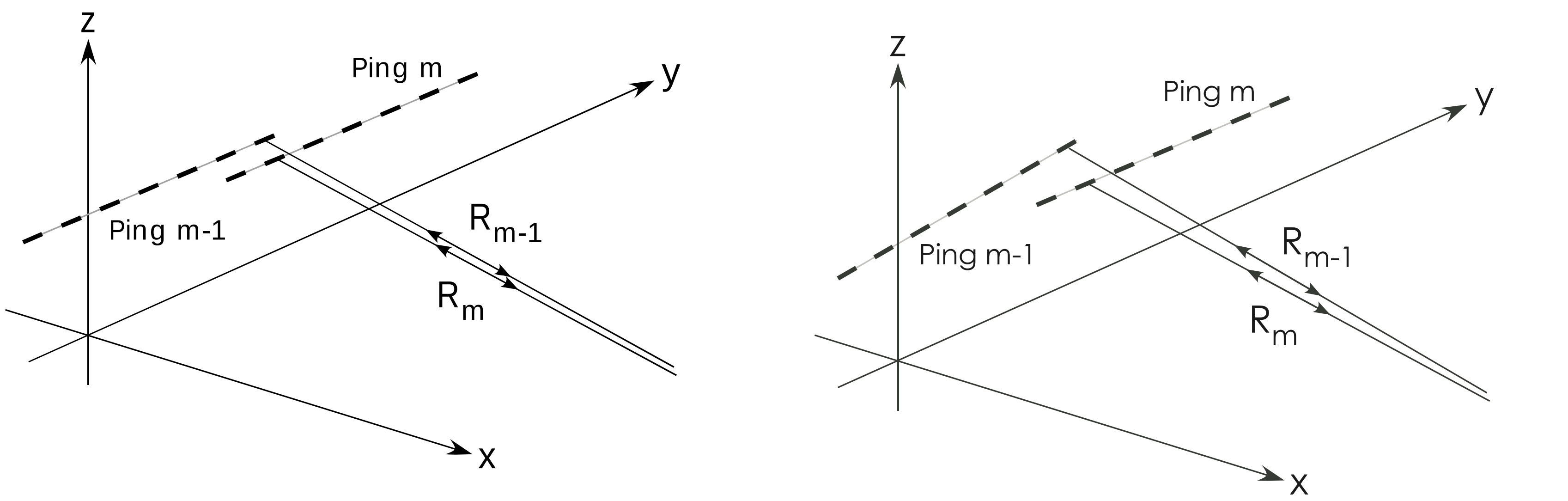
	Motion Estimation	Interferometry
Known	Bottom Contour	Sensor Locations
Unknown	Sensor Locations	Bottom Contour

We assume a flat sea floor. No one has yet shown if this can be relaxed, and to what extent.



(Line drawing from Andrea Bellettini of NURC)

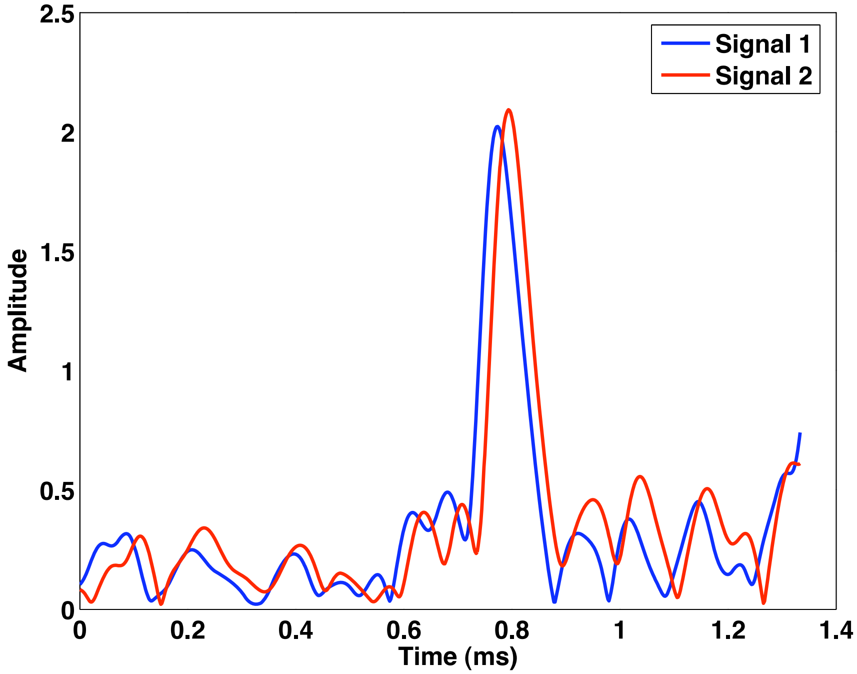
Time Delay Estimation



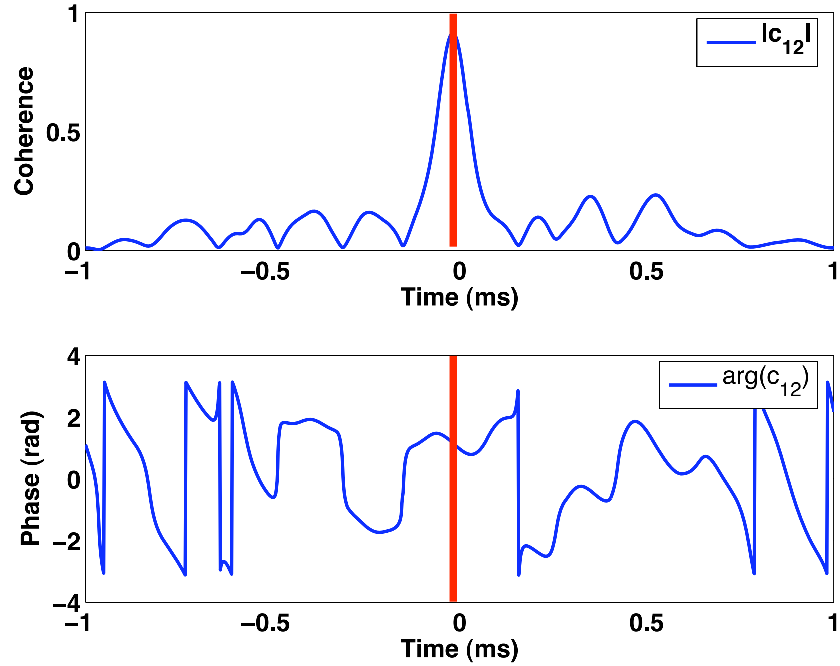
Relative displacement between two pings induces a time shift with respect to the overlapping channel returns.

Time Delay Estimation

Magnitude of Signals X_1 and X_2



Magnitude and phase of ρ_{12}



Note: The cross-correlation coefficient ρ_{12} is complex because we operate on the complex, baseband signals.

Time Delay Estimation

Bellettini documents the Cramer-Rao lower bounds on the standard deviation of the coarse and fine delays:

$$\sigma_c = \frac{\sqrt{3}}{\pi} \cdot \frac{1}{B} \cdot \frac{1}{\sqrt{BT}} \sqrt{\frac{1}{\rho} + \frac{1}{2\rho^2}}$$

$$\sigma_f = \frac{1}{2\pi f_0} \cdot \frac{1}{\sqrt{BT}} \sqrt{\frac{1}{\rho} + \frac{1}{2\rho^2}}$$

For the 120 kHz SAS with $|\rho_{12}| = 0.9$ and a 1 m correlation window, the CRLBs are:

$$\sigma_c \approx \lambda/10$$

$$\sigma_f \approx \lambda/144$$

Time Delay Estimation

Times delays are estimated using a sliding window that moves down range and computes a local correlation and time delay. We use a sliding window for the following reasons:

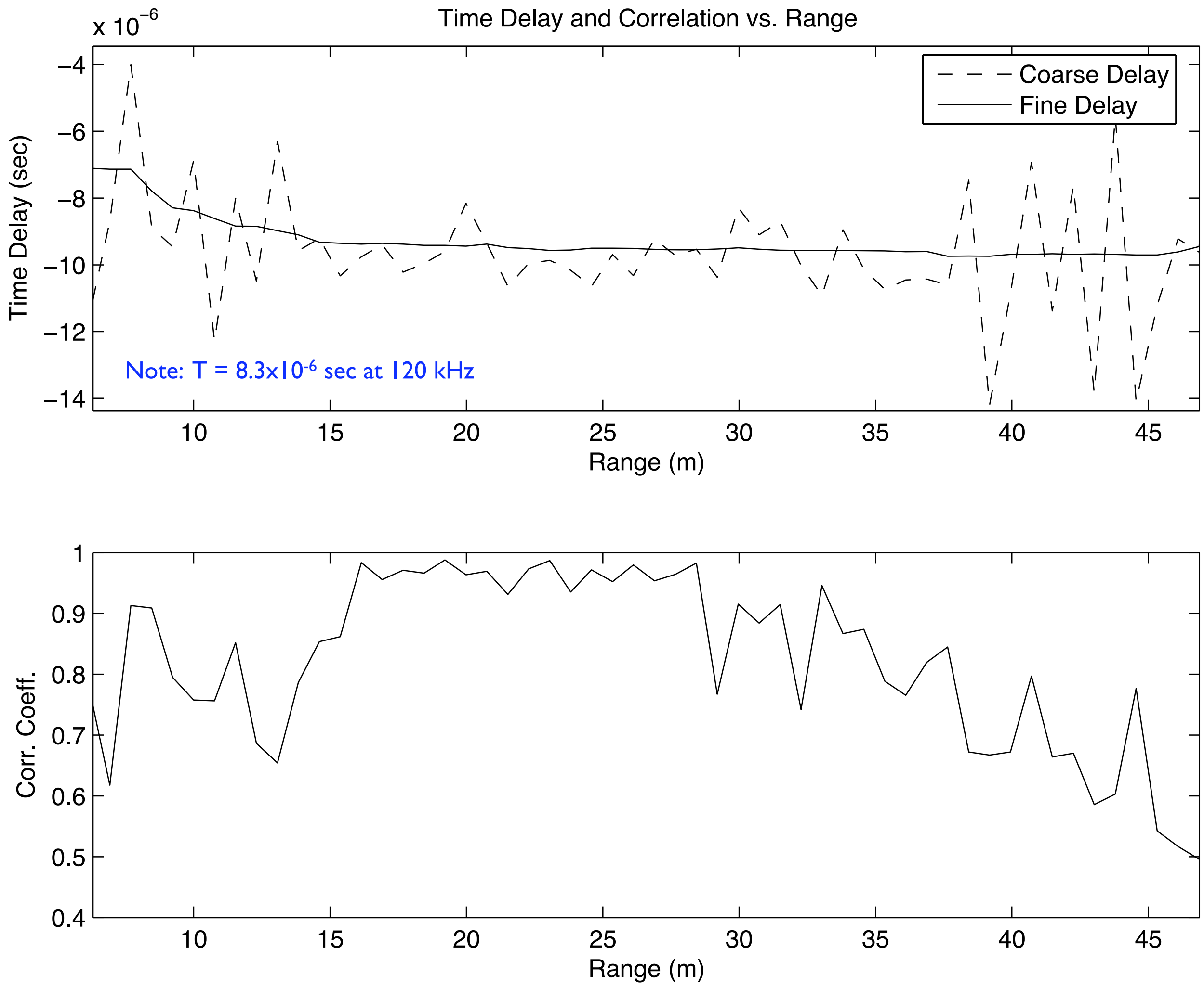
1) The time delay varies with range,
2) The correlation may be poor in localized regions.

If the sonar parameters are fixed, the CRLBs are determined by the correlation and the window length. This argues for an adaptive windowing scheme that adjusts T in response to local conditions.

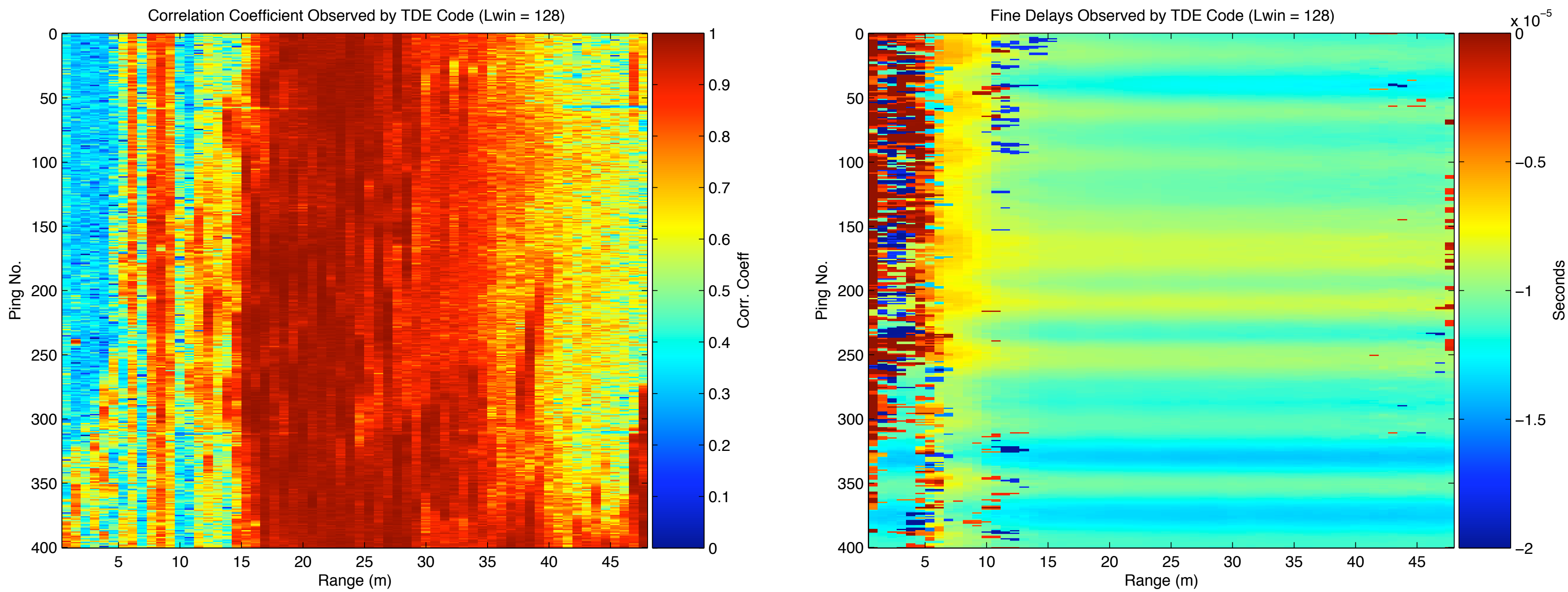
$$\sigma_c = \frac{\sqrt{3}}{\pi} \cdot \frac{1}{B} \cdot \frac{1}{\sqrt{BT}} \sqrt{\frac{1}{\rho} + \frac{1}{2\rho^2}}$$

$$\sigma_f = \frac{1}{2\pi f_0} \cdot \frac{1}{\sqrt{BT}} \sqrt{\frac{1}{\rho} + \frac{1}{2\rho^2}}$$

Time Delay Estimation



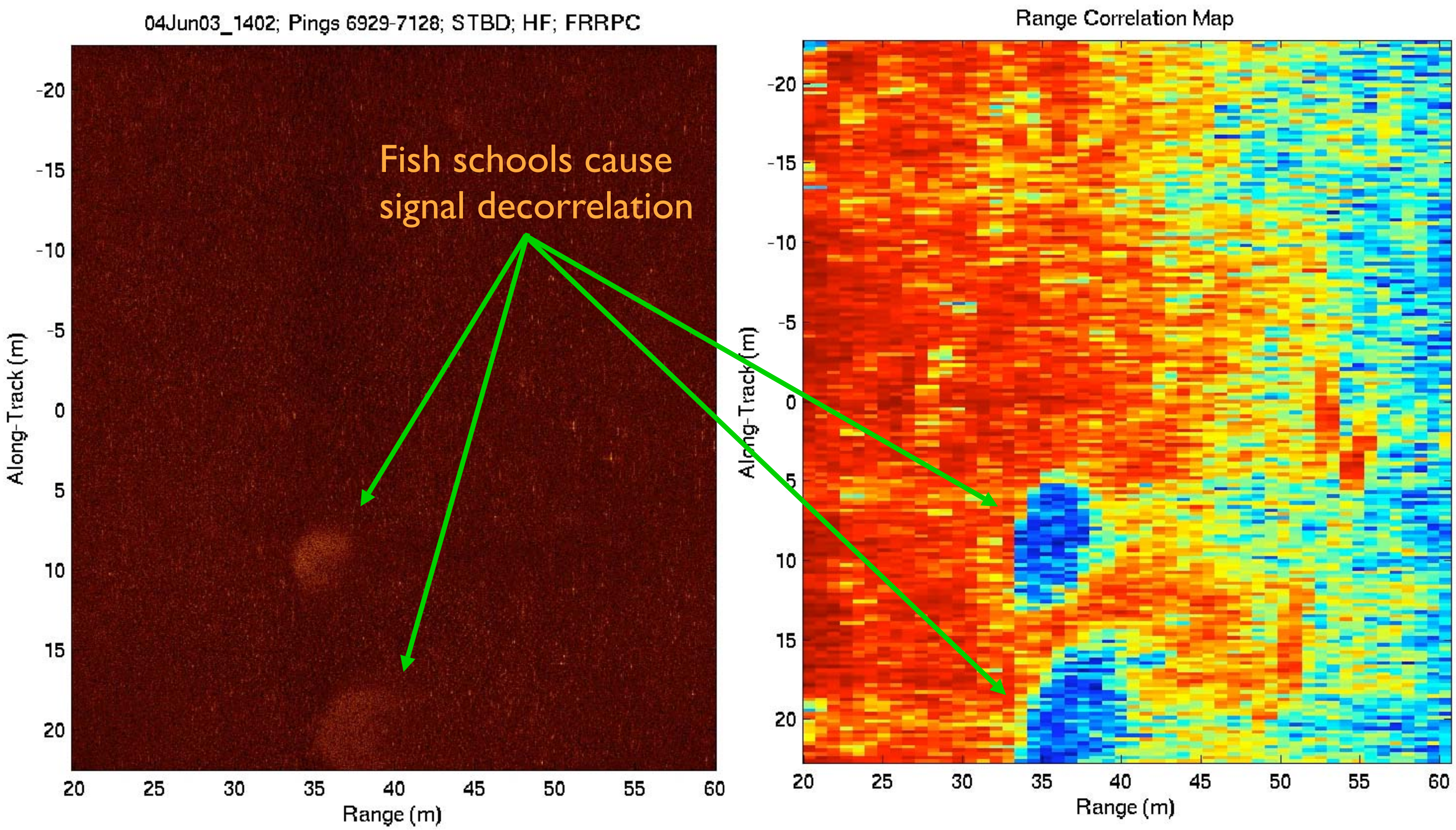
Time Delay Estimation



Magnitude of ρ_{12}

Fine time delay estimates

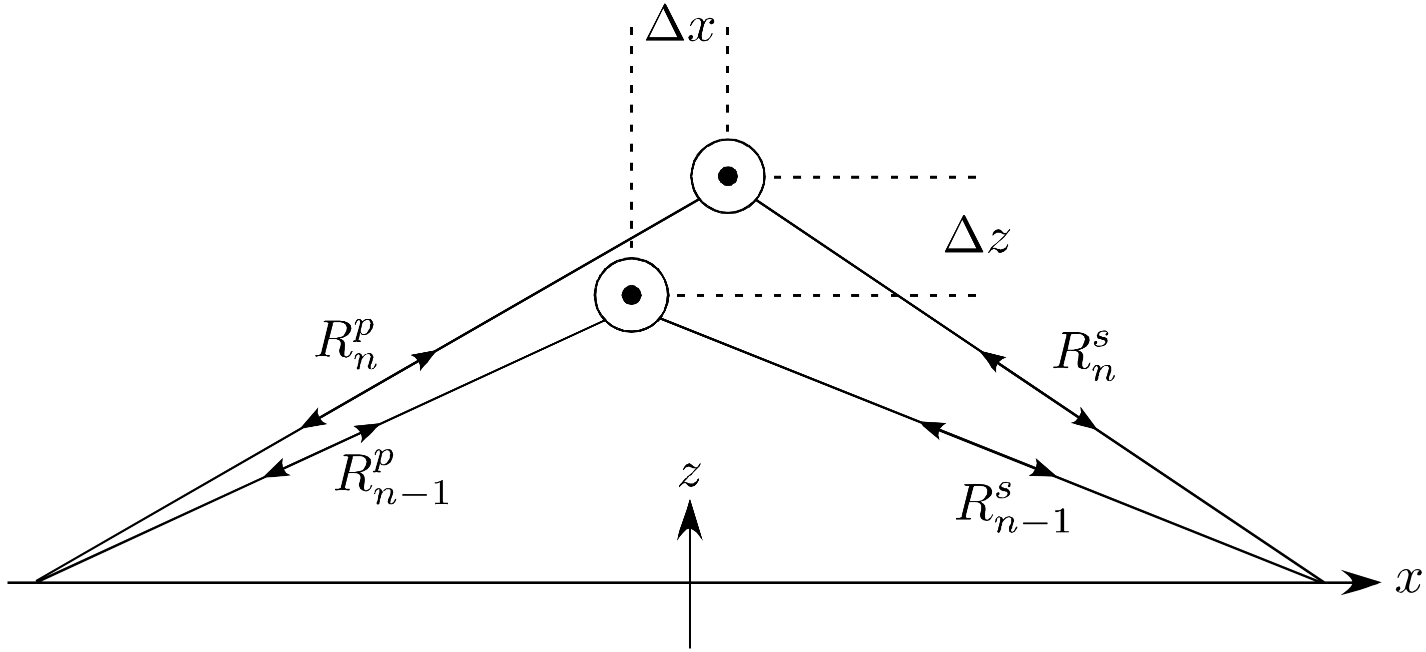
Time Delay Estimation in the Presence of Biologics



Motion Estimation

- The time delays are not the motion. They describe a range-dependent curve that depends on the motion.
- An inverse problem: We measure the time delays and use them with a model to solve for the vehicle motion.
- Two techniques in use at NSWC-PC:
  - Explicit solution (based on stop-and-hop).
  - Nonlinear least squares solution.
- Other SAS groups do it differently, depending on their philosophy.

Explicit Solution



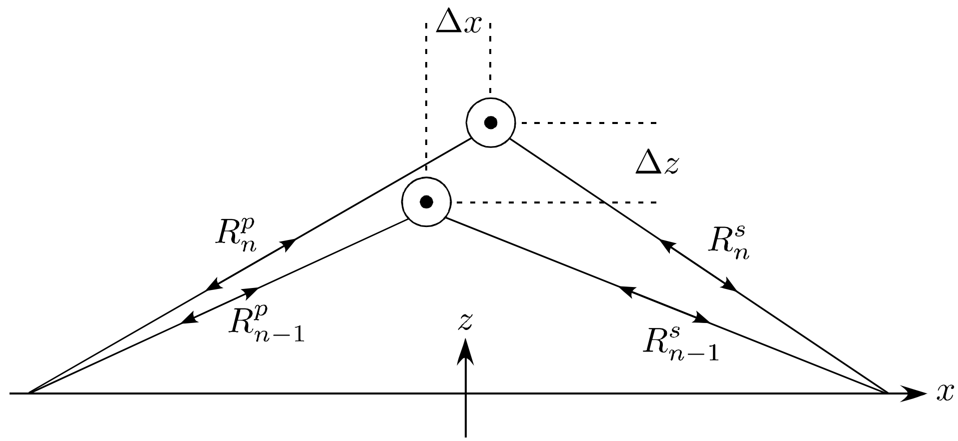
Imagine the vehicle moving into the screen. Because the redundant channels overlap in the *y* direction, we can construct the 2d figure above. Furthermore, assume that the array is motionless between transmit and receive.

Explicit Solution

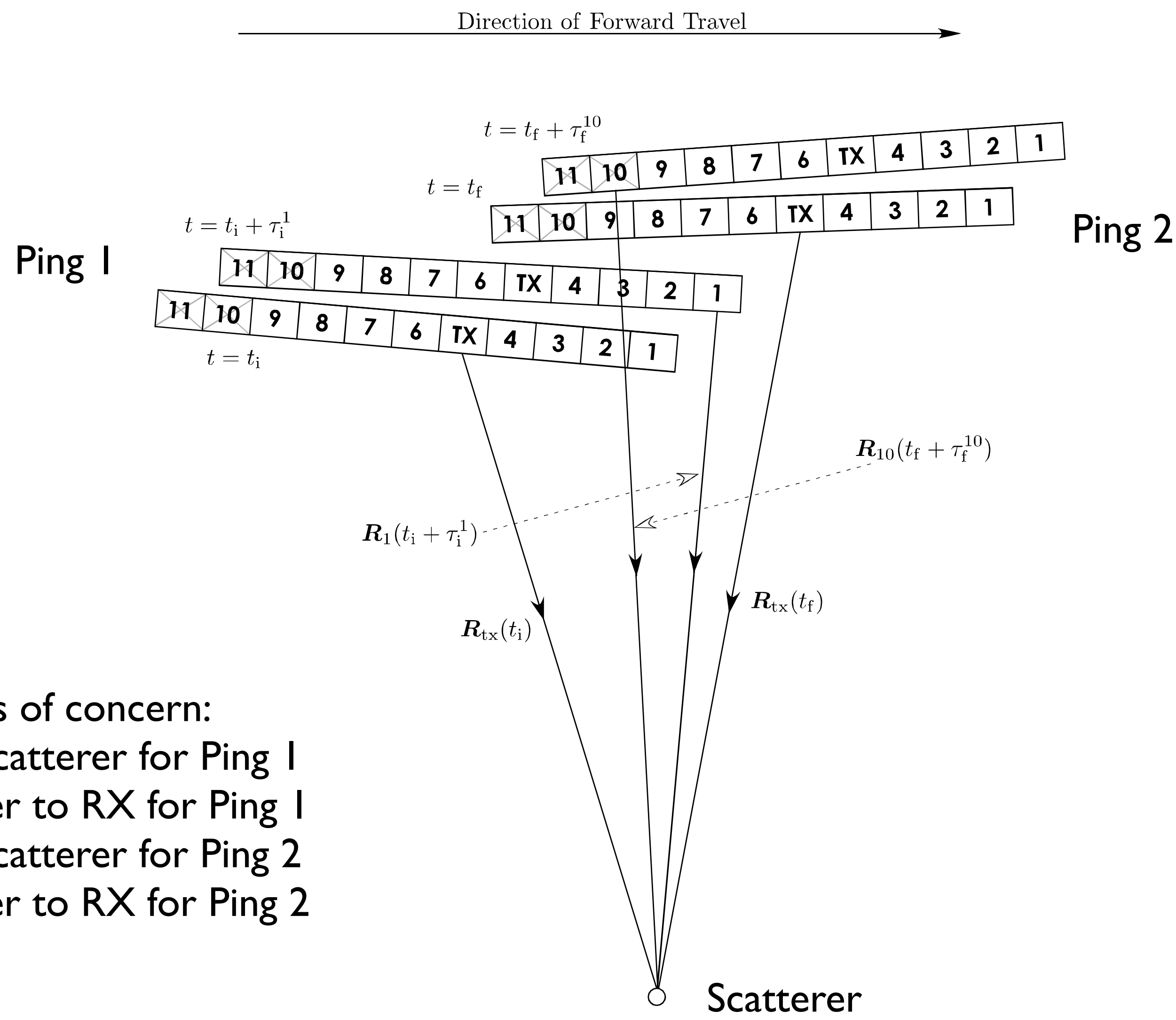
We assume no surge error. Thus, we have two unknowns ($[v_x\ v_z]^T$) and two equations (port and starboard). This computation is repeated at each sliding window location and the $[v_x\ v_z]^T$ are averaged using ρ_{12} as weights.

$$v_x = \frac{-1}{s_x \Delta t}\left(\frac{\alpha_s^2 - \alpha_p^2}{16} + s_x \hat{p}_{10,x}\right)$$

$$v_z = (-b + \sqrt{b^2 - 4ac})/(2a)$$



Nonlinear Least Squares



Four ranges of concern:

1) TX to scatterer for Ping 1
2) Scatterer to RX for Ping 1
3) TX to scatterer for Ping 2
4) Scatterer to RX for Ping 2

Nonlinear Least Squares

This equation represents the observed time delay as a function of the motion:

$$
\begin{aligned}
c\Delta\tau^{1:10} &= c(\tau_{\mathrm{f}}^{10} - \tau_{\mathrm{i}}^{1}) \\
&= |\boldsymbol{s} - \{\boldsymbol{x}(t_{\mathrm{i}}) + \Delta t \boldsymbol{v}(t_{\mathrm{i}})\} - \{\Phi(t_{\mathrm{i}})\boldsymbol{d}_{\mathrm{tx}} + \Delta t \boldsymbol{\omega}(t_i) \times \Phi(t_{\mathrm{i}})\boldsymbol{d}_{\mathrm{tx}}\}| \\
&\quad - |\boldsymbol{s} - \boldsymbol{x}(t_{\mathrm{i}}) - \Phi(t_{\mathrm{i}})\boldsymbol{d}_{\mathrm{tx}}| \\
&\quad + \left|\boldsymbol{s} - \left\{\boldsymbol{x}(t_{\mathrm{i}}) + (\Delta t + \tau_{\mathrm{f}}^{10})\boldsymbol{v}(t_{\mathrm{i}})\right\} - \left\{\Phi(t_{\mathrm{i}})\boldsymbol{d}_{10} + (\Delta t + \tau_{\mathrm{f}}^{10})\boldsymbol{\omega}(t_{\mathrm{i}}) \times \Phi(t_{\mathrm{i}})\boldsymbol{d}_{10}\right\}\right| \\
&\quad - \left|\boldsymbol{s} - \left(\boldsymbol{x}(t_{\mathrm{i}}) + \tau_{\mathrm{i}}^{1}\boldsymbol{v}(t_{\mathrm{i}})\right) - \left(\Phi(t_{\mathrm{i}})\boldsymbol{d}_{1} + \tau_{\mathrm{i}}^{1}\boldsymbol{\omega}(t_{\mathrm{i}}) \times \Phi(t_{\mathrm{i}})\boldsymbol{d}_{1}\right)\right| \\
&= \boldsymbol{R}_{\mathrm{tx}}(t_{\mathrm{f}}) - \boldsymbol{R}_{\mathrm{tx}}(t_{\mathrm{i}}) + \boldsymbol{R}_{10}(t_{\mathrm{f}} + \tau_{\mathrm{f}}^{10}) - \boldsymbol{R}_{1}(t_{\mathrm{i}} + \tau_{\mathrm{i}}^{1}) \\
&= \boldsymbol{R}_{\mathrm{a}} - \boldsymbol{R}_{\mathrm{b}} + \boldsymbol{R}_{\mathrm{c}} - \boldsymbol{R}_{\mathrm{d}},
\end{aligned}
$$

Four ranges of concern:

1) TX to scatterer for Ping 1 (R_b)
2) Scatterer to RX for Ping 1 (R_a)
3) TX to scatterer for Ping 2 (R_d)
4) Scatterer to RX for Ping 2 (R_c)

Motion Estimation

- The previous equation has three unknowns. They are the components of the (translational) velocity vector. The orientation and angular velocity is assumed to be known from the vehicle INS.
- The solution is obtained using nonlinear least squares (via Newton's Method, see below).

$$x_{k+1} = x_k - \frac{f(x_k)}{f'(x_k)}$$

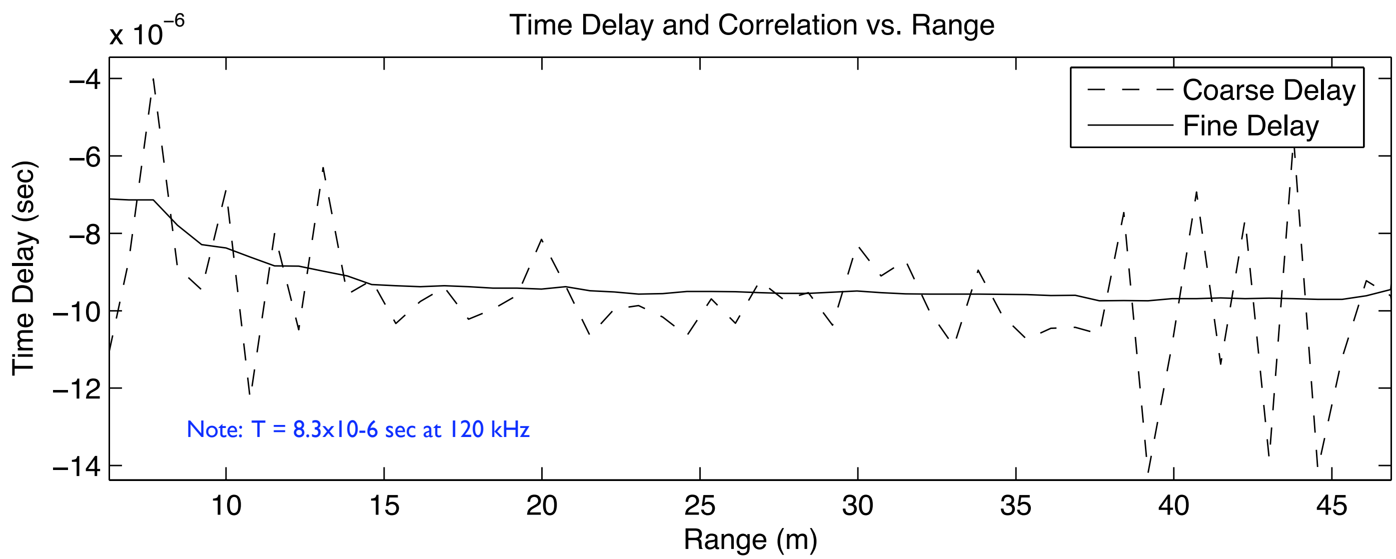
Scalar Case

$$\mathbf{x}_{k+1} = \mathbf{x}_k - J(\mathbf{x}_k)^{-1} F(\mathbf{x}_k)$$

Vector Case

Motion Estimation

- In light of the previous slide, the curve shown below is a function of three variables: $f(v_x,v_y,v_z)$.
- We find $[v_x\ v_y\ v_z]^T$ for each ping and then integrate to obtain the motion history for the scene.



Comparison

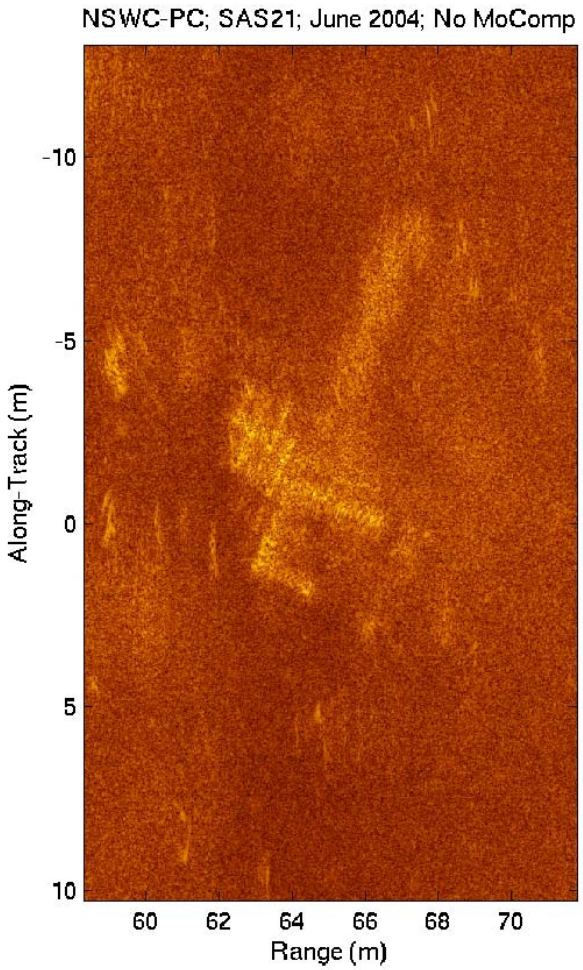
Explicit solution

- + Explicit (non-iterative and fast)
- + Simple to understand and implement
- + A proven technique (10's of km of SAS sonar track observed)
- – Requires a two-sided sonar
- – Assumes stop-and-hop (not good at long ranges)

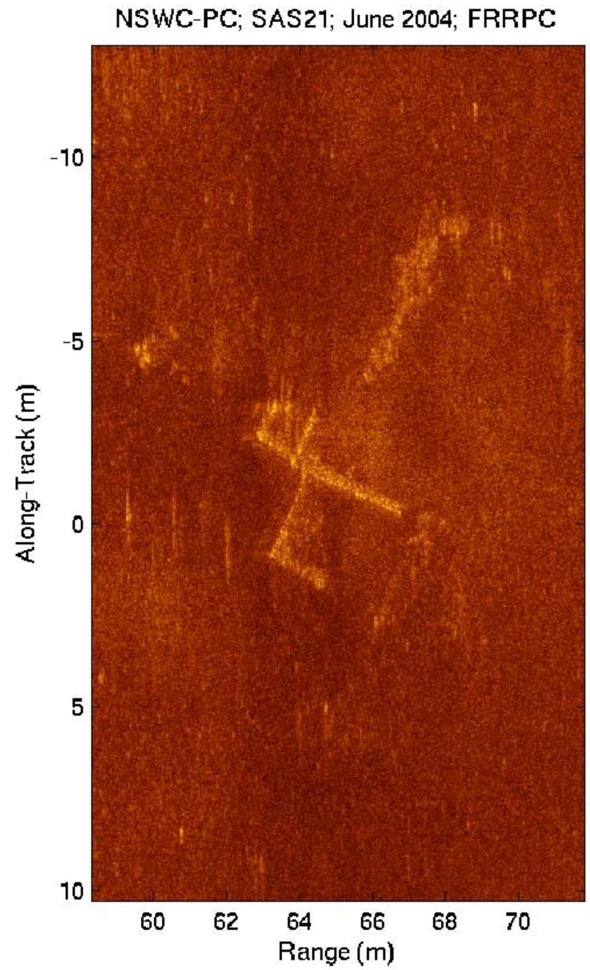
Nonlinear least squares

- + Works with a single-sided sonar (a major benefit)
- + No stop-and-hop assumption
- + When it works, it works really well
- – Iterative, so we must watch for convergence
- – Existence and uniqueness of solutions not yet proven
- – Care must be taken to ensure robust implementation

SAS Imagery

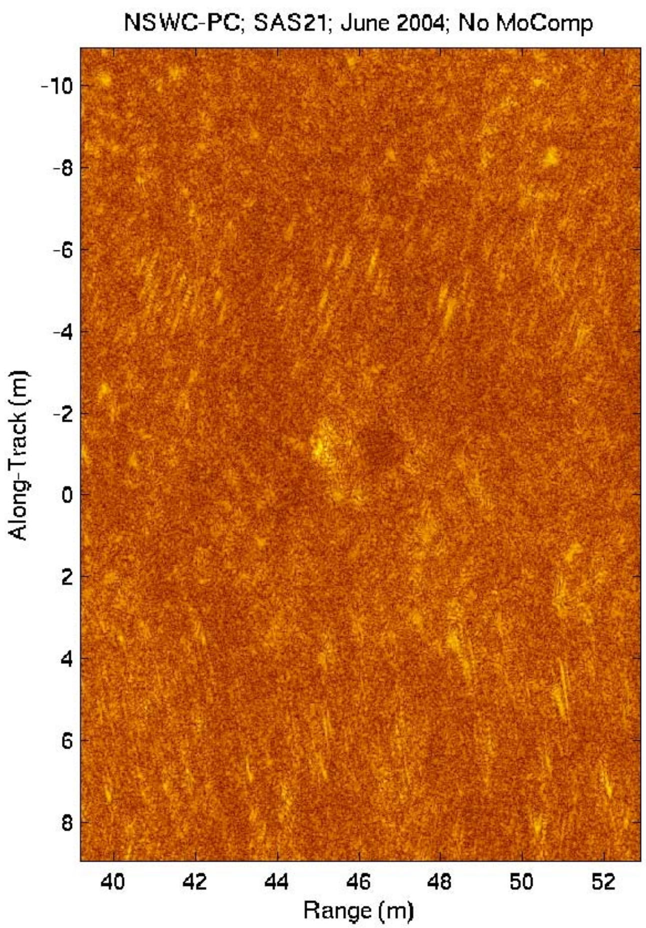


No MoComp

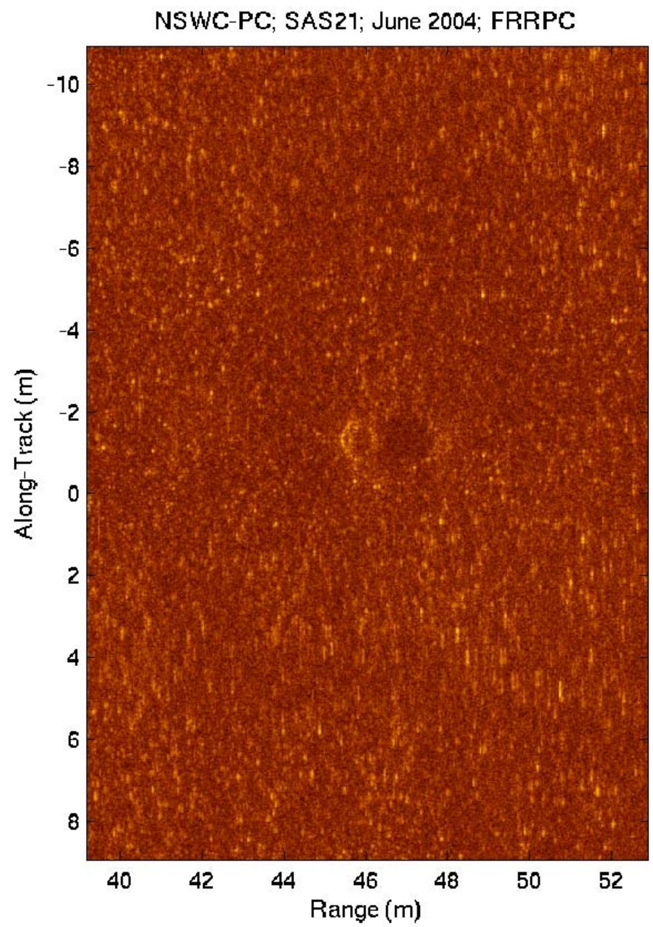


Fully-Resolved RPC

SAS Imagery

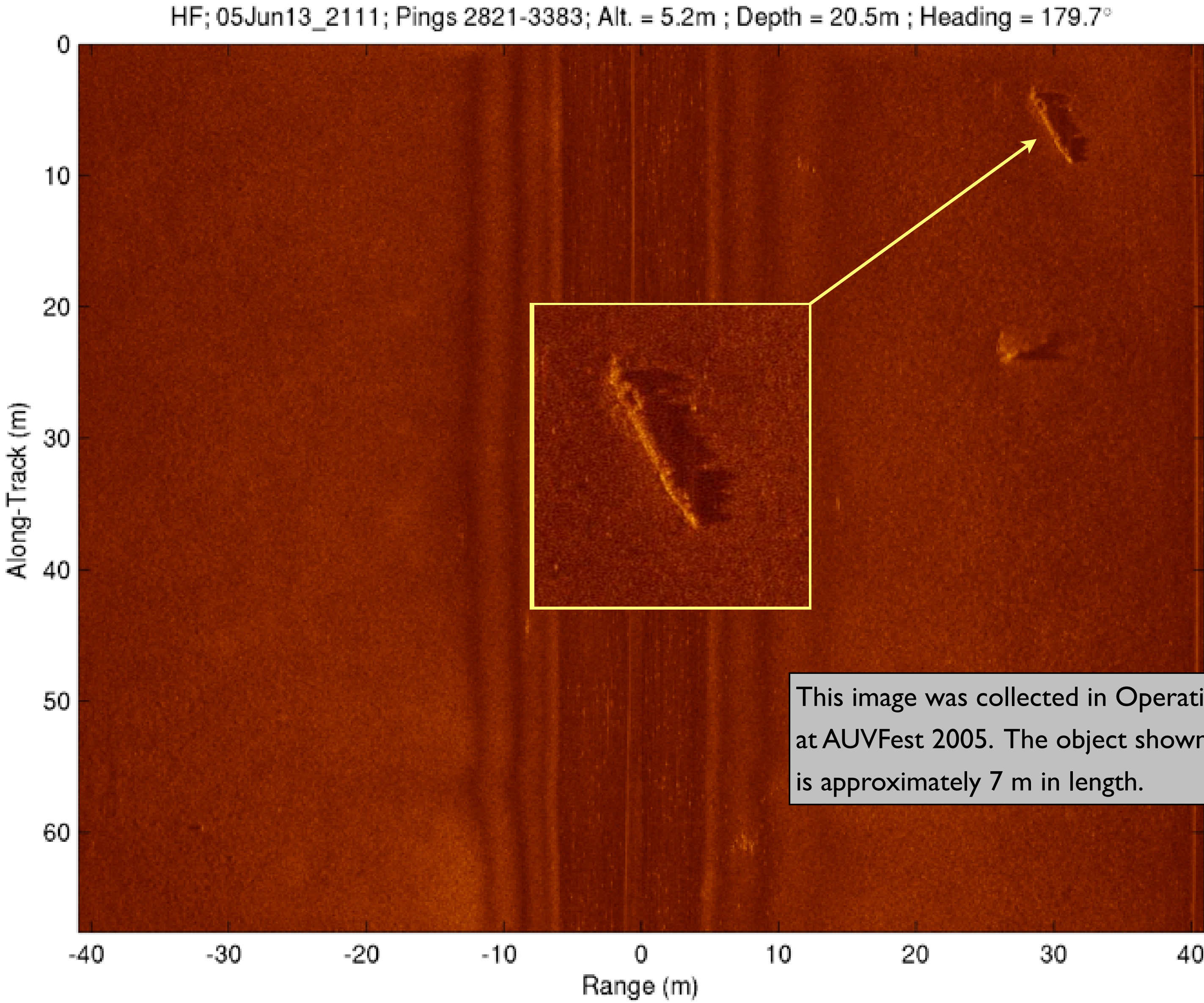


No MoComp



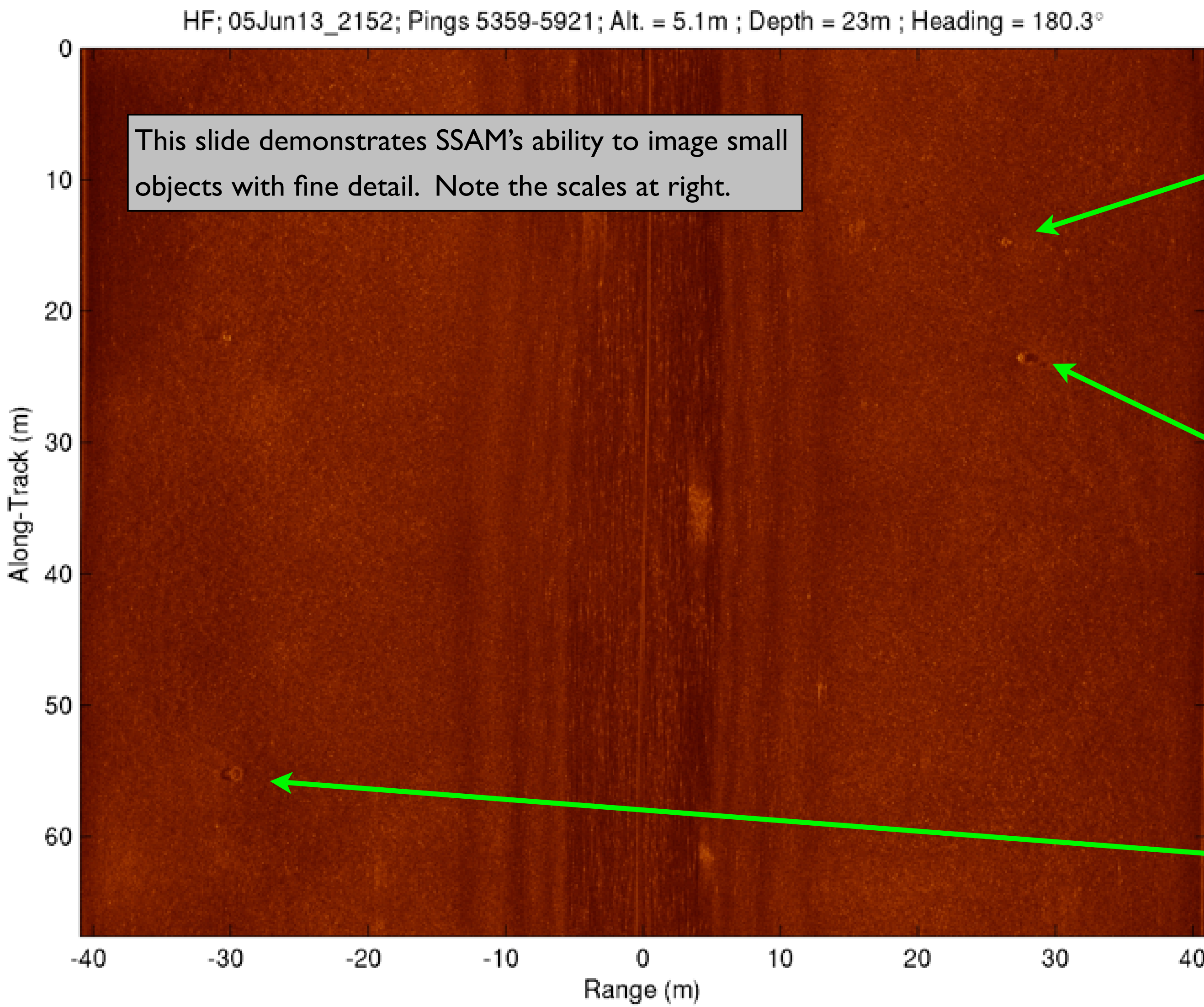
Fully-Resolved RPC

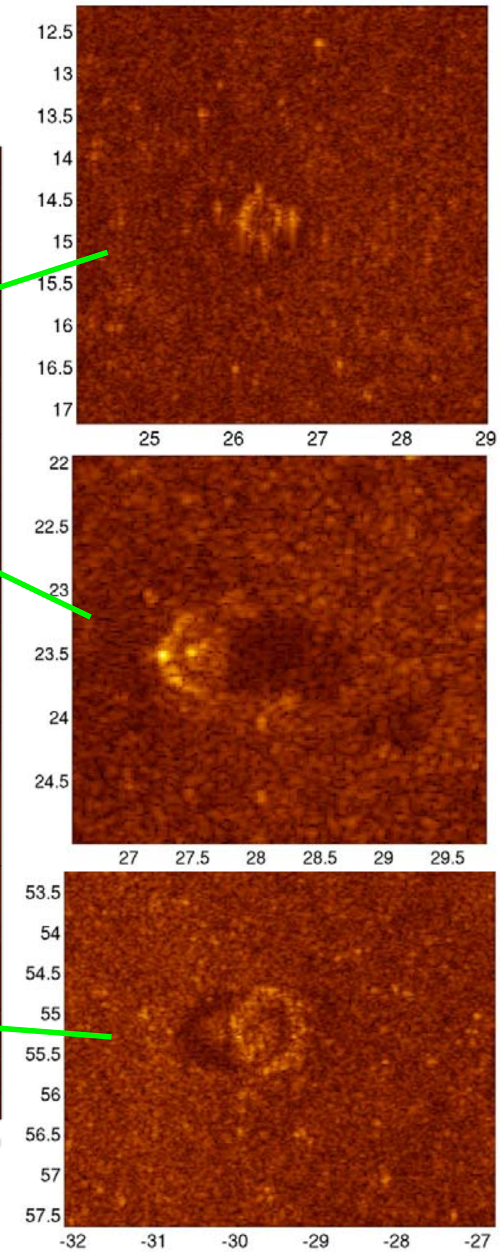
SAS Imagery



This image was collected in Operational Area 4 at AUVFest 2005. The object shown in the inset is approximately 7 m in length.

SAS Imagery


HF; 05Jun13_2152; Pings 5359-5921; Alt. = 5.1m ; Depth = 23m ; Heading = 180.3°
This slide demonstrates SSAM's ability to image small objects with fine detail. Note the scales at right.
Along-Track (m)
0
10
20
30
40
50
60
-40
-30
-20
-10
0
10
20
30
40
Range (m)


12.5
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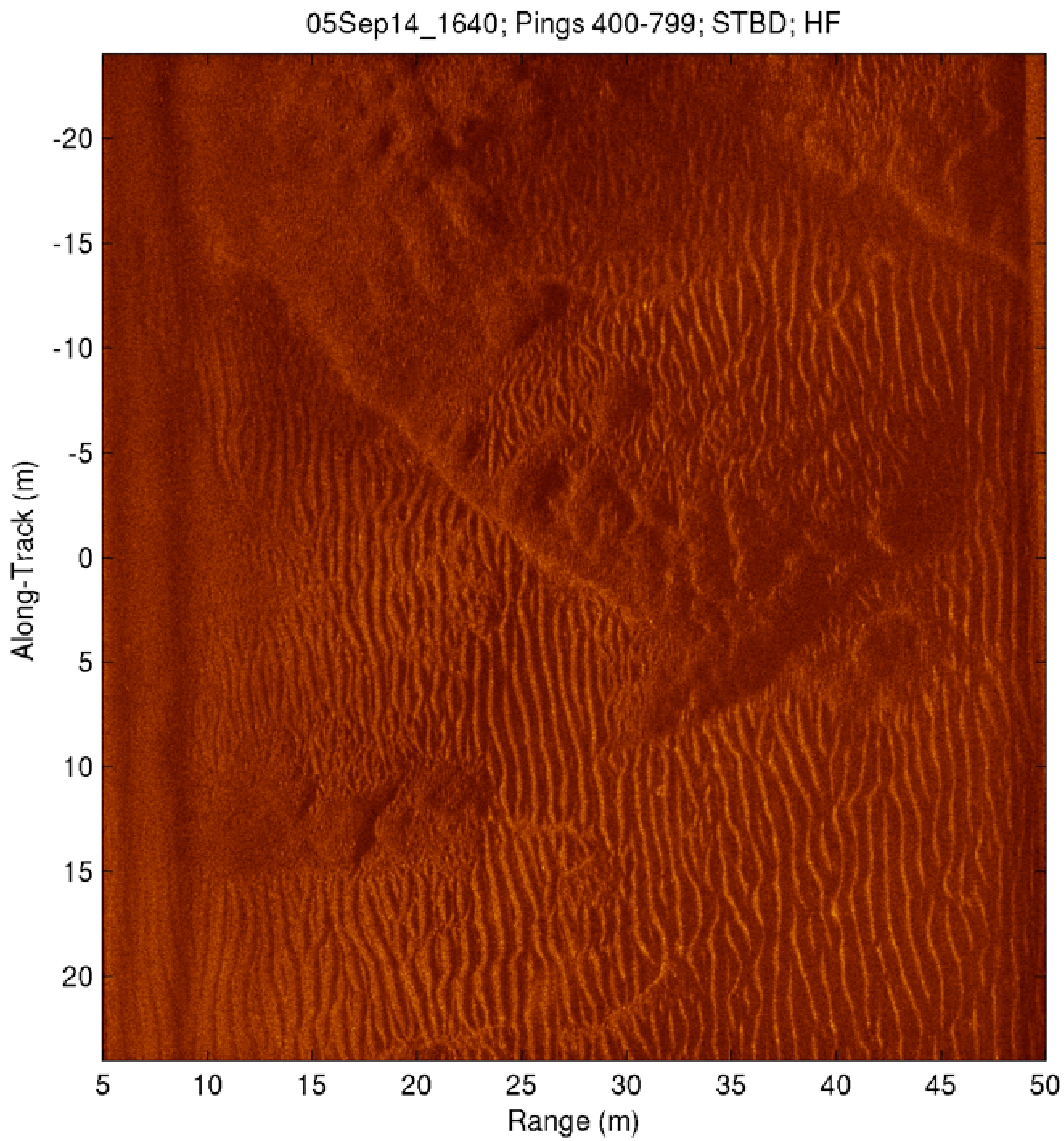
-27

SAS Imagery



05Sep14_1640; Pings 400-799; STBD; HF
Along-Track (m)
-20
-15
-10
-5
0
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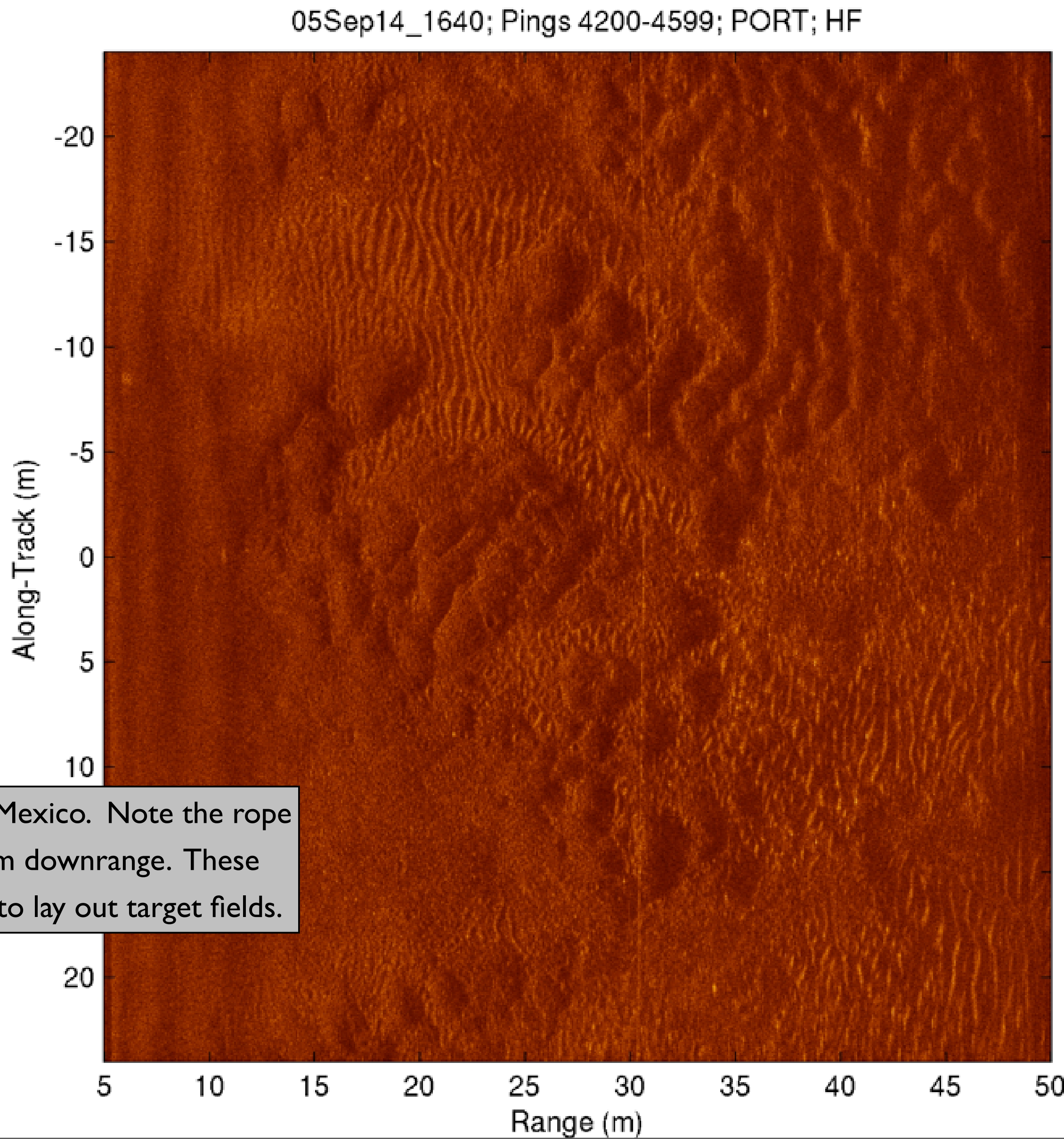
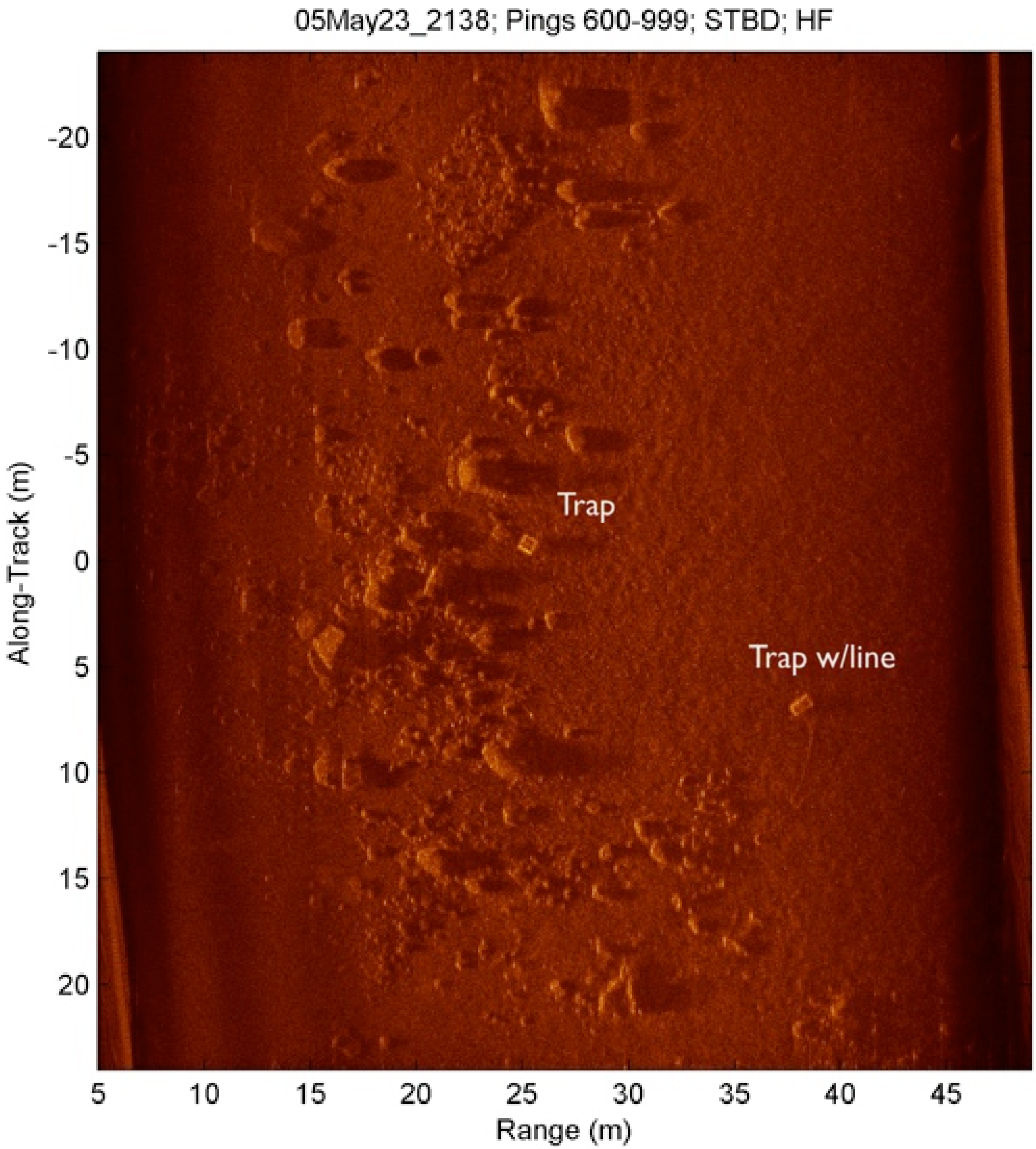
25
30
35
40
45
50
Range (m)

SAS Imagery



Sea floor in the Gulf of Mexico. Note the rope running vertically at 30 m downrange. These lines are used by divers to lay out target fields.

SAS Imagery



The image to the left was collected in Buzzard's Bay, Cape Cod. Among the rocks can be seen a pair of lobster traps. The line attached to one of them is clearly visible.

SSAM Overview

- Simultaneous dual frequency band operation:
  - HF band = 105 - 135 kHz, 1" x 1" res.
  - LF Band = 8 - 52 kHz, 3" x 3" res.
- DC Capabilities against proud & slightly buried targets.
- Array elements used for MoComp = 2.
- Range = 90/Vel (45 meters @ 2 m/sec).
  - L_{SA} HF band = 11 meters
  - L_{SA} LF band = 22 meters

SAS Applications

- Currently driven by the need to accurately map large areas of the sea floor for the purposes of minehunting.
- Fine-scale oceanography.
- Surveying (erosion, pipelines, etc).
- US Navy SAS is occasionally called upon for finding debris/wreckage.
- Underwater crime scene investigation.

SAS Players

- United States
  - Naval Surface Warfare Center- Panama City
  - Allied Signal Technology (formerly DTI)
  - Penn State University
  - Northrup-Grumman
- New Zealand: University of Canterbury, Christchurch
- NATO Undersea Research Center: La Spezia, Italy
- United Kingdom: QinetiQ
- Norway: FFI (Forsvarets Forskningsinstitutt)
- France: GESMA (Groupe de Etudes sous Marines de la Atlantique)

Current SAS Needs

- Analysis of NLLS motion estimation:
  - Existence and uniqueness of solutions.
  - Estimate statistics w.r.t. 3 components of the velocity, and weight accordingly when combining with other motion sensor outputs.
- Detailed analysis of sensitivity of image quality in response to 6-DOF motion.
- Adaptive windowing scheme for time delay estimation.
- What is the best "redundant array" for motion estimation? By using a 2d overlapping section, what motions can we estimate and to what accuracy? What is the relationship to interferometry?
- *Broadband low-frequency sonar processing (e.g., sub-bottom imaging, object material characterization, internal structure visualization).*

The End / Questions