Observations of Fluorescent Dye Dispersion in the Seasonal Pycnocline Using Airborne Lidar

Miles A. Sundermeyer

Daniel A. Birch

Experimental Center for Environmental Lidar (EXCEL)
School for Marine Science & Technology
University of Massachusetts Dartmouth

James R. Ledwell, Eugene A. Terray

Woods Hole Oceanographic Institution

Brian Concannon

Naval Air Systems Command (NAVAIR)

Murray Levine, Stephen Pierce, Brandy Cervantes

Oregon State University, Corvallis

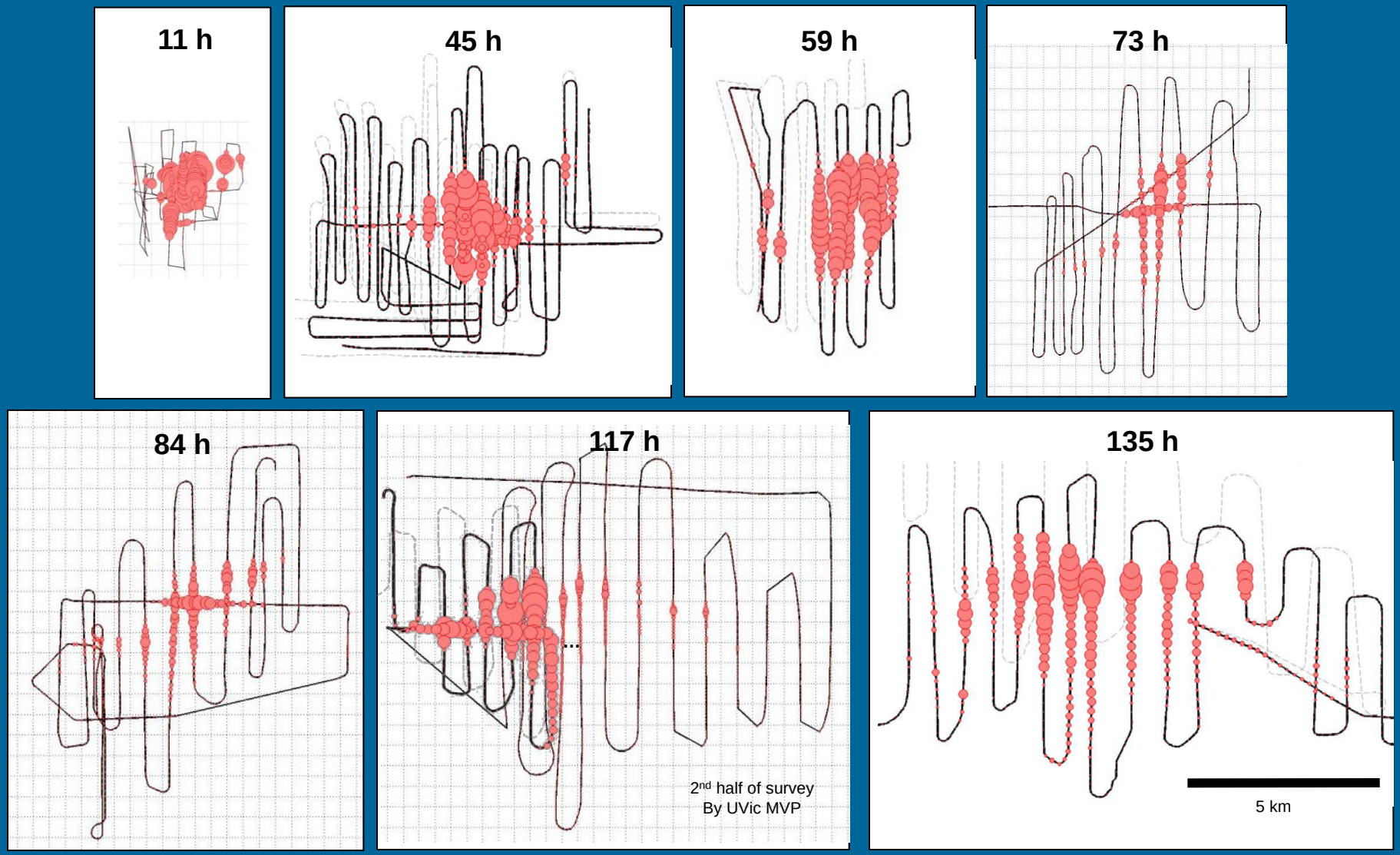
Supported by:

National Science Foundation: OCE-0751734, OCE-0751653

Office of Naval Research Grants: N00014-09-1-0194, N00014-09-1-0175

Ocean Mixing Studies

LatMix 2011: Rhodamine Experiment 1

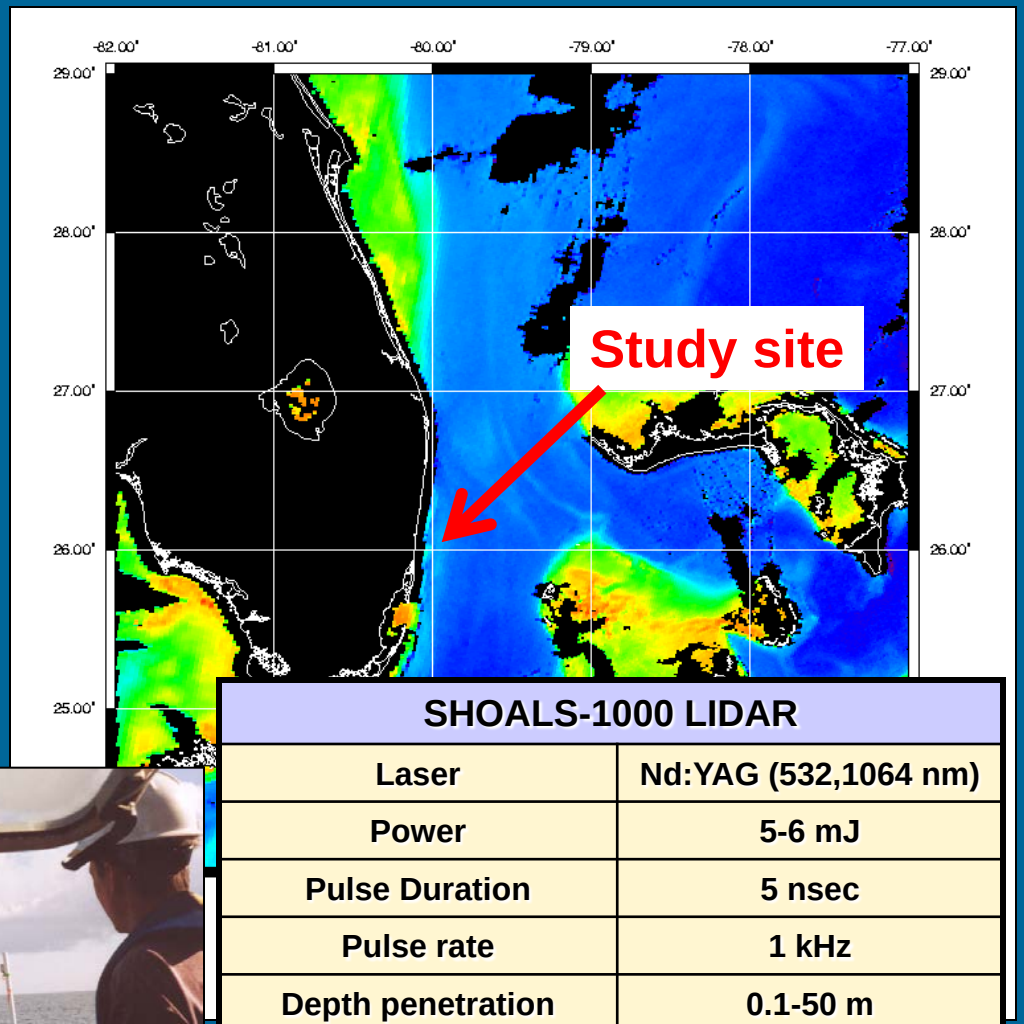


Sundermeyer

2004 Dye Lidar Proof of Concept

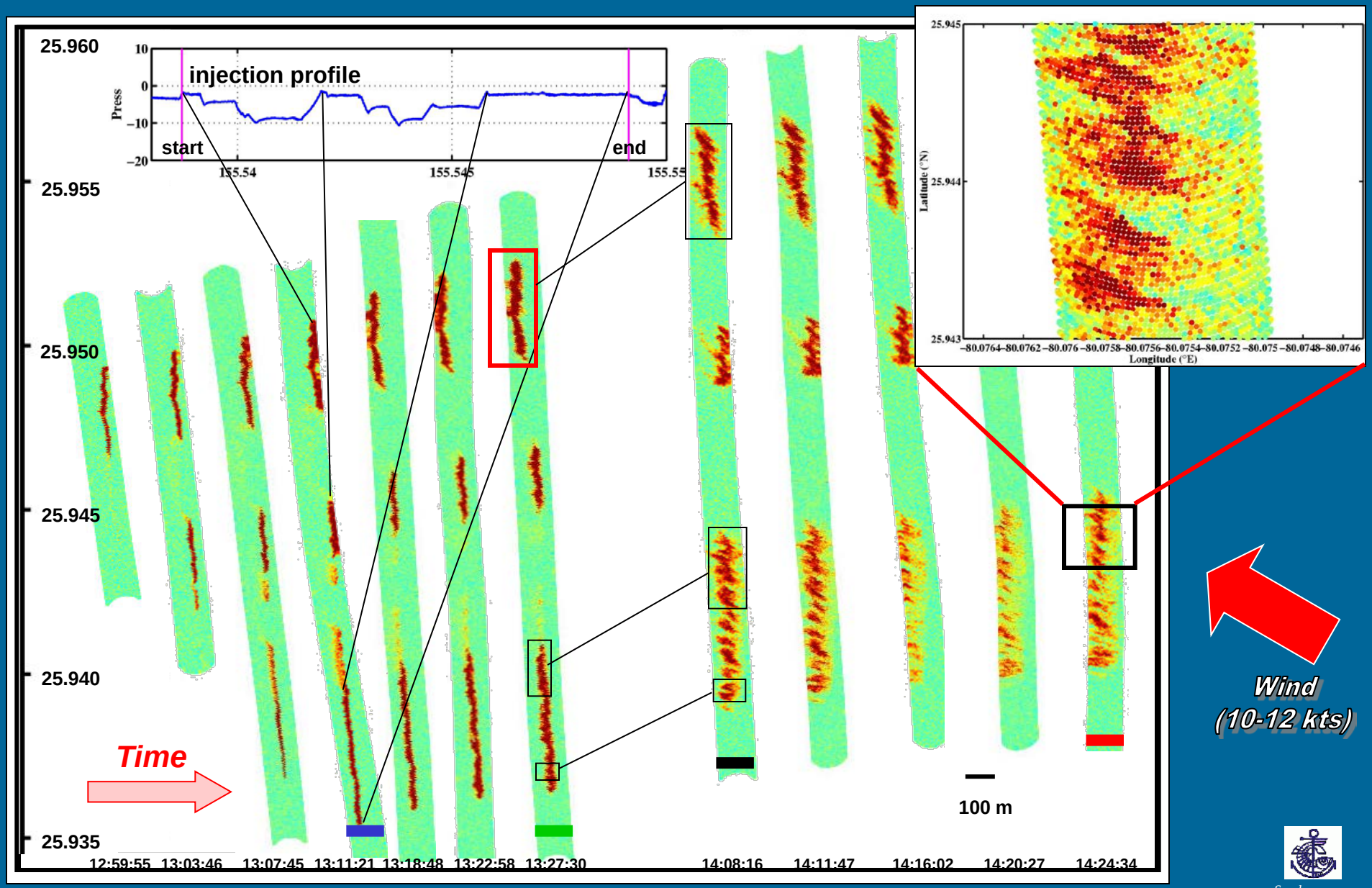
(Sundermeyer et al., 2007)

- Two near-surface releases: 5 kg Rhodamine WT injected in a continuous streak.
- Dye mapped over 1-2 hours using fluorometer & CTD towed from ship, plus airborne LIDAR.



SHOALS-1000 LIDAR	
Laser	Nd:YAG (532,1064 nm)
Power	5-6 mJ
Pulse Duration	5 nsec
Pulse rate	1 kHz
Depth penetration	0.1-50 m
Horizontal accuracy	2.5 m
Operating altitude	200-400 m
Swath width	Variable to 0.58 x alt.

Dye Streak as Viewed from Airborne LIDAR, FL 2004



Sundermeyer

Inversion for Absolute Dye Concentration

(Terray et al., 2005; Sundermeyer et al., 2007)

Laser channel:

$$I_{532}(z) = I_{S532}(z)\, e^{-2\int_0^z \alpha_{D532} C(z')dz'}$$

$$\Rightarrow \quad C(z) = \frac{1}{2\alpha_{D532}} \frac{d}{dz} \ln\left(\frac{I_{S532}(z)}{I_{532}(z)}\right)$$

Fluorescence channel:

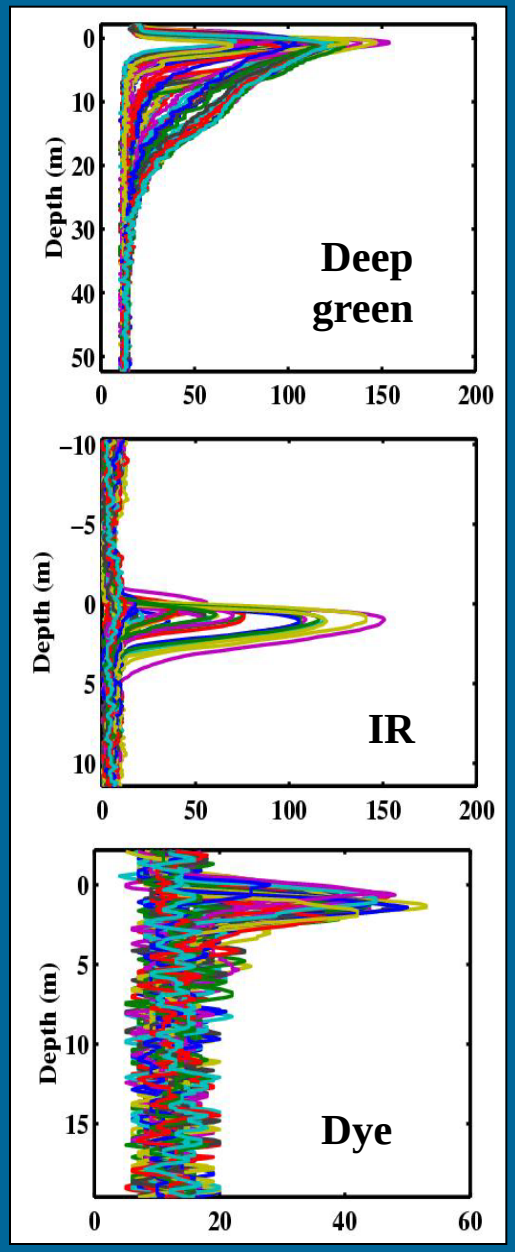
$$I(z) = P\, C(z)\, e^{-2\int_0^0 (\alpha_D C(z') + k_s)dz'}$$

$$\Rightarrow \quad \frac{dC}{dz} - \alpha_D C^2 - g(z)C = 0$$

where: $$g(z) = \frac{1}{I_{580}} \frac{dI_{580}}{dz} + k_S(z)$$

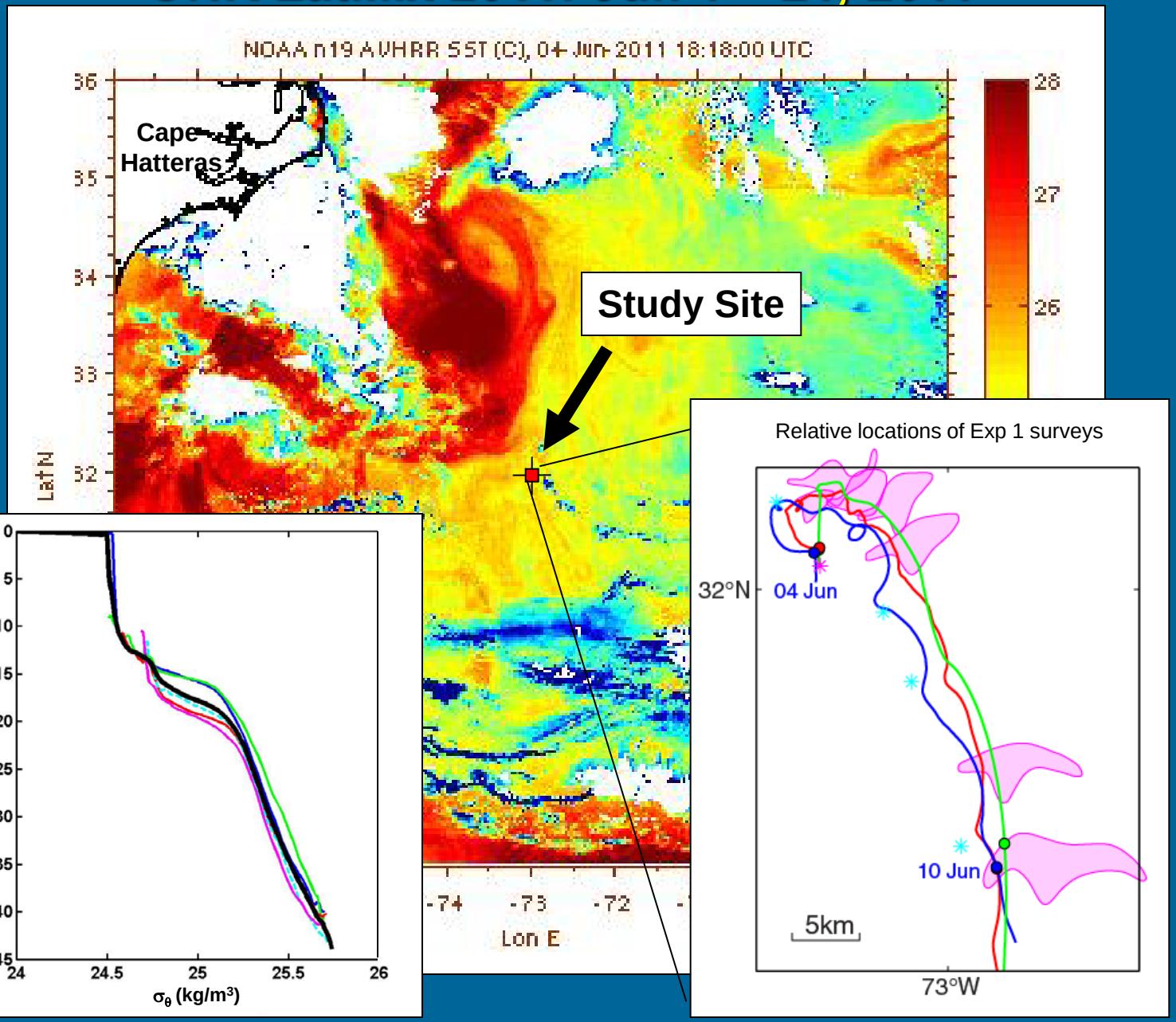
Combining the two, obtain absolute dye concentration:

$$C = C(z | C_r, \alpha_D, k_S(z), I_{580}(z)) \qquad \varepsilon^2 = \| I - I_{580} \|^2 + w \| C - C_{532} \|^2$$



Sundermeyer

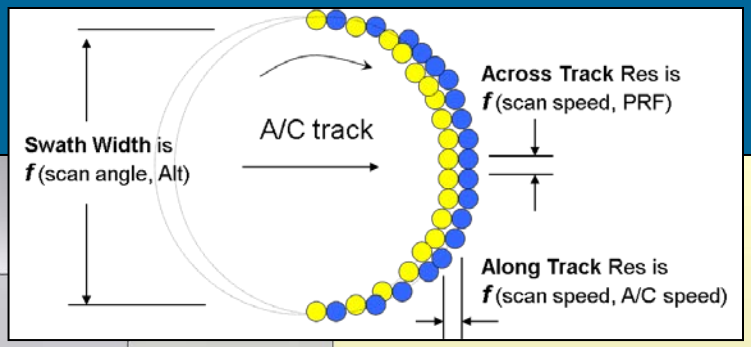
ONR LatMix 2011: Jun 1 – 21, 2011

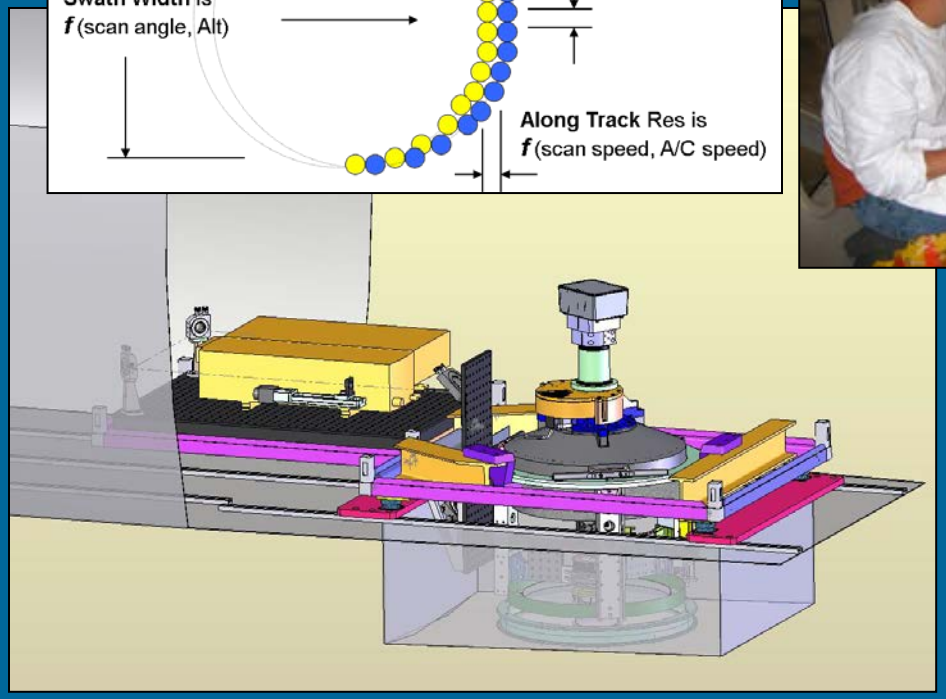


Sundermeyer

ONR LatMix 2011: LIDAR Surveys

NAVAIR LIDAR System Specifications



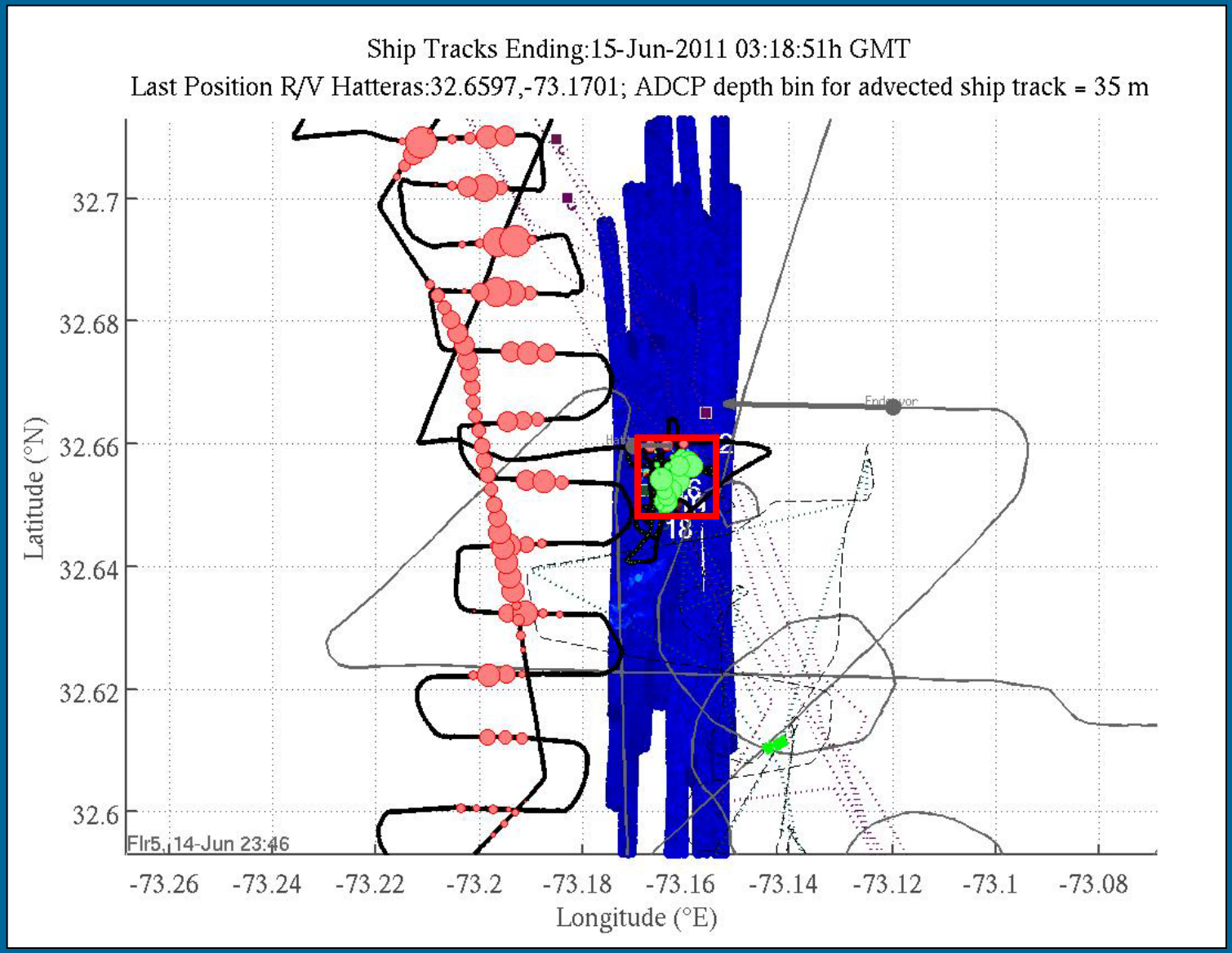


- 480 nm Ti:Sapphire laser
- 1 kHz rep rate
- 30 ns pulse chopped to 10 ns
- 1 mJ per pulse (0.2)
- 2 receive channels

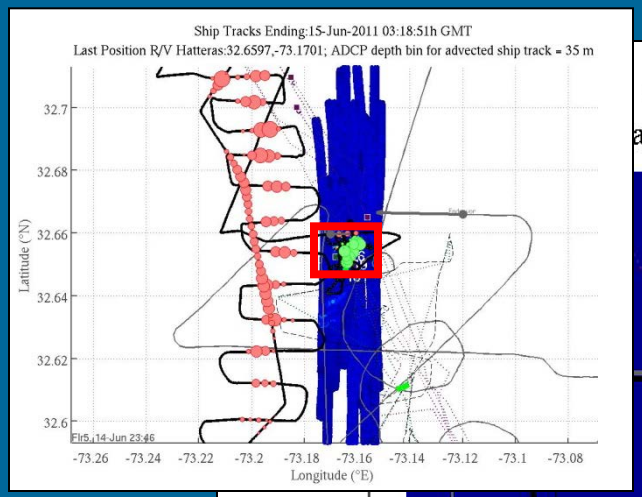
- 10 m horizontal resolution
- 1 m vertical resolution
- 200 m swath @ 300 m alt.
- 100 m/s along-track

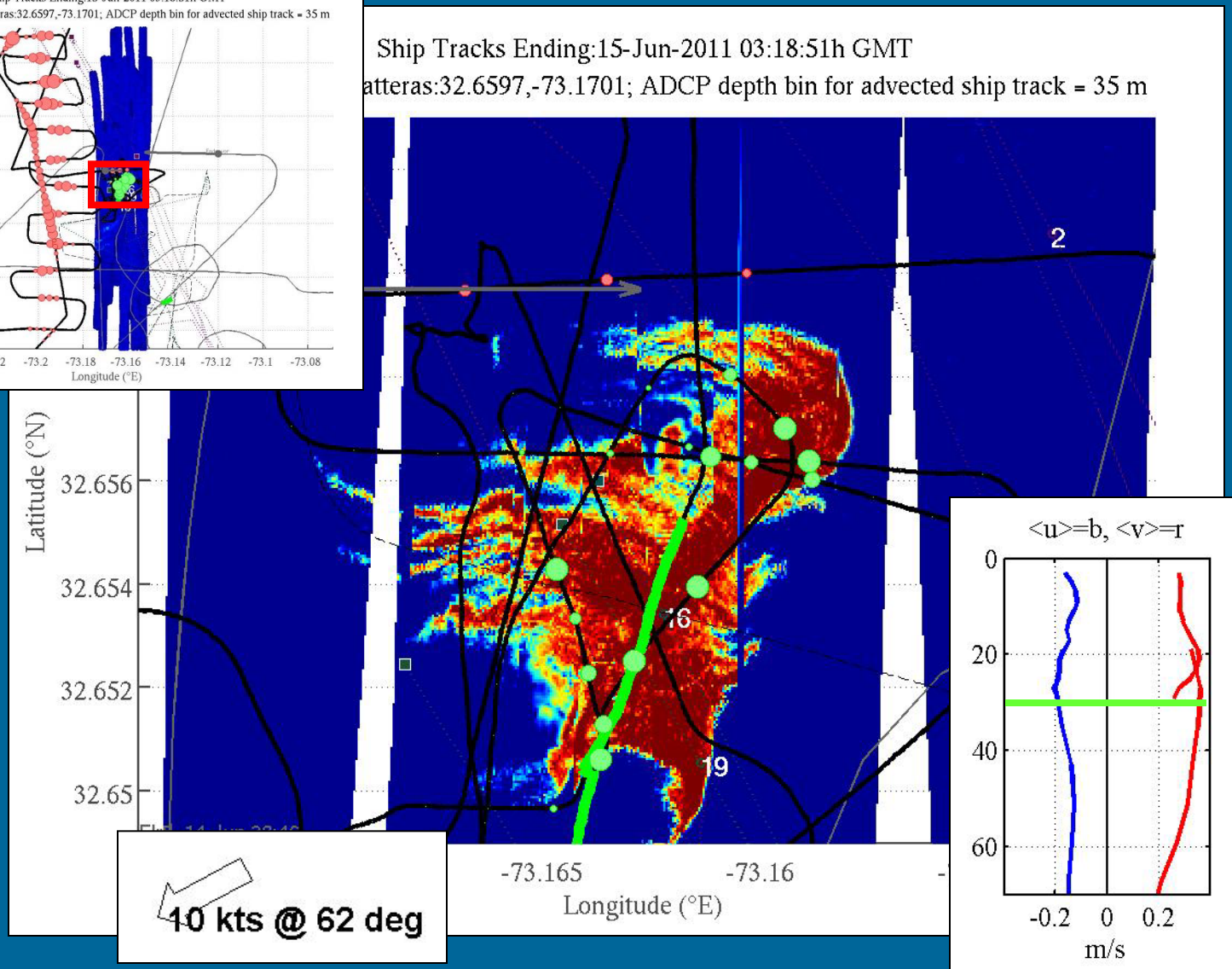
Sundermeyer

ONR LatMix 2011: June 15, Flr5



ONR LatMix 2011: June 15, Flr5

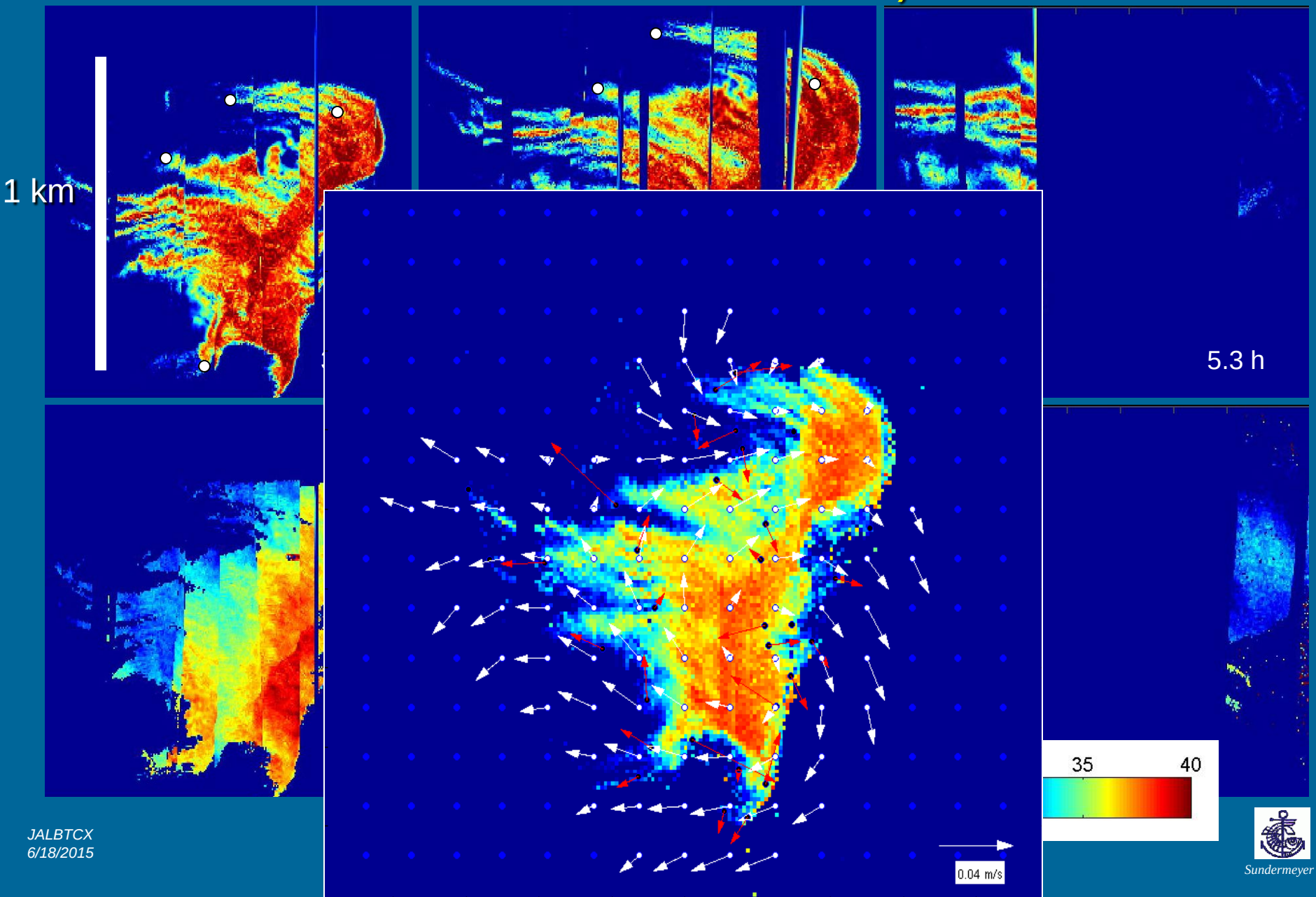




Inject
@ 31 m

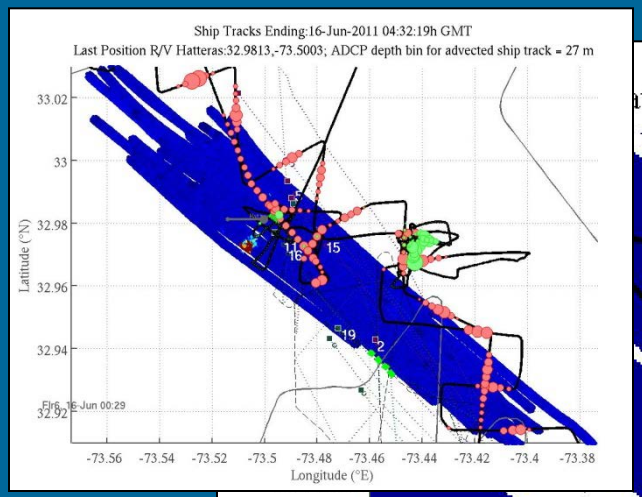
Sundermeyer

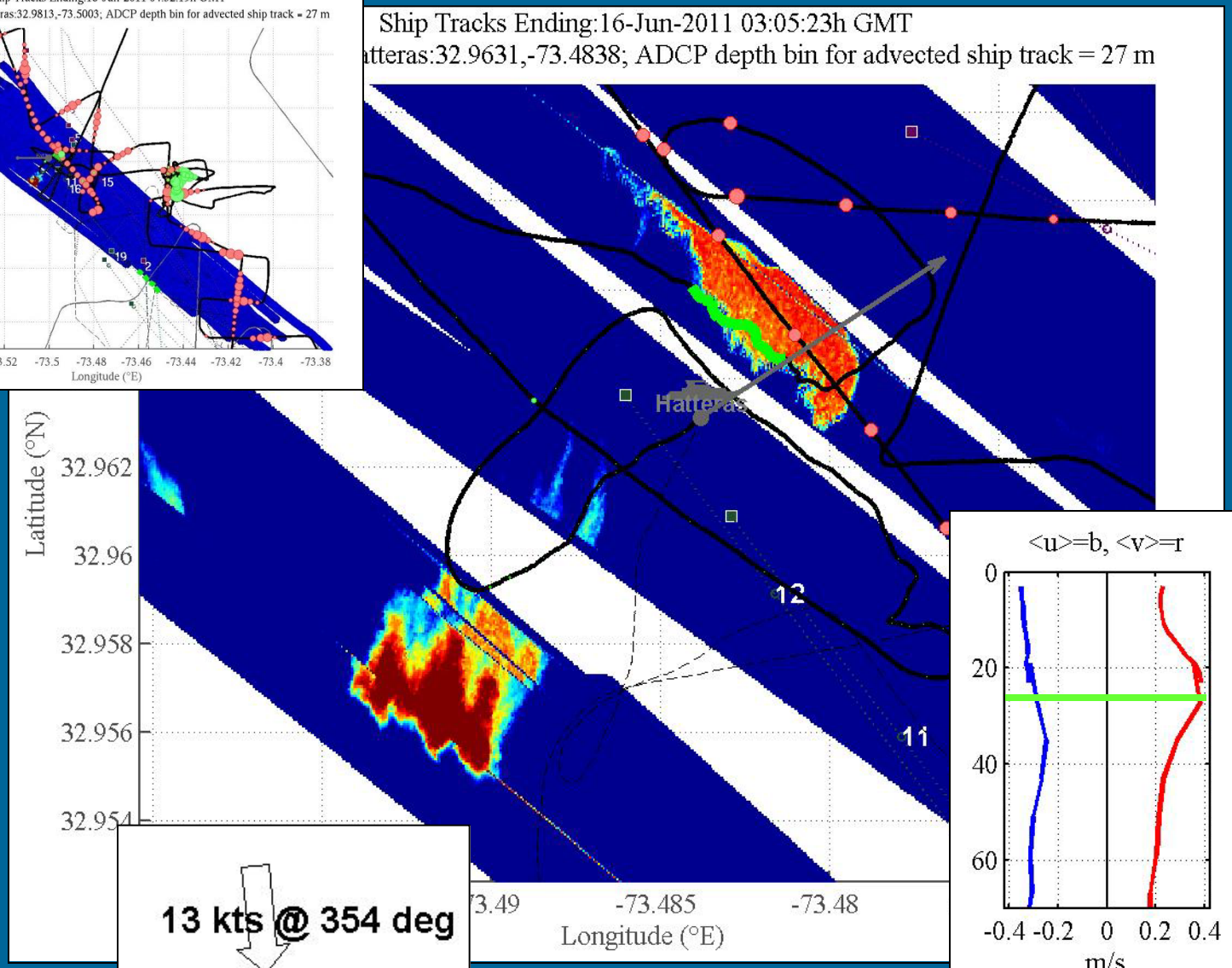
ONR LatMix 2011: June 15, Flr5 +

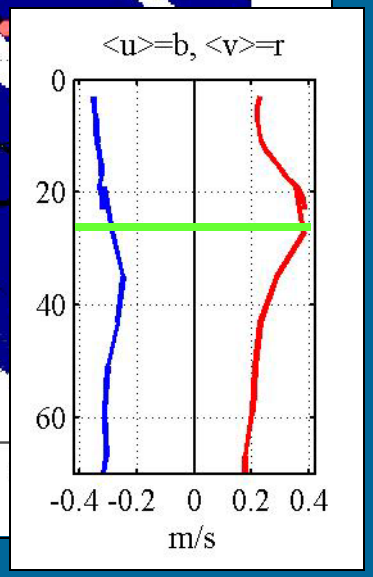


Sundermeyer

ONR LatMix 2011: June 16, Flr6, 6a



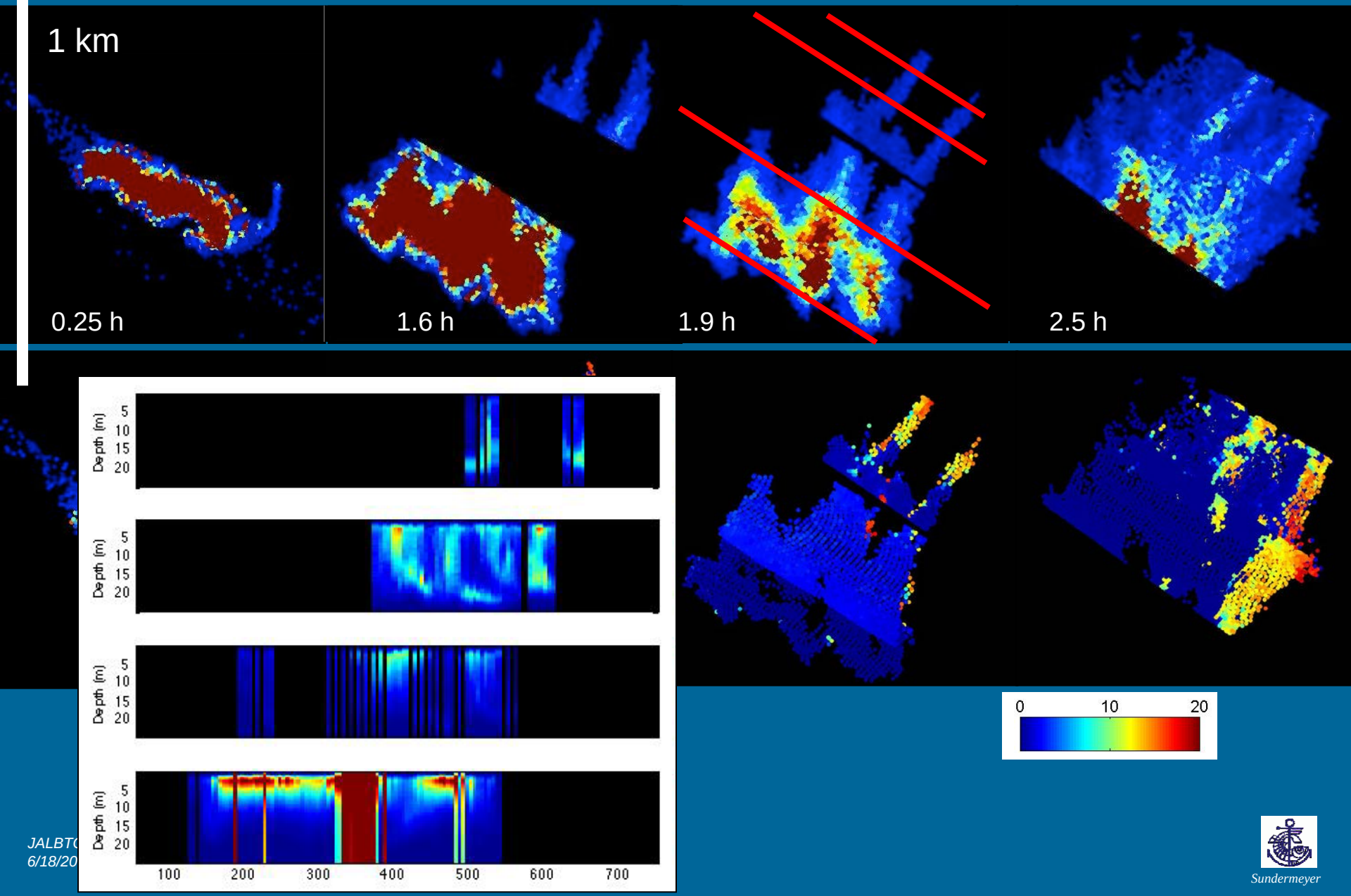




Inject
@ 27 m
& 3.5 m

Sundermeyer

LatMix 2011: June 16, Flr6, 6a



Sundermeyer

Inverting for Absolute Dye Concentration (ppb)

Assume

- downward propagating Gaussian laser pulse
- exponential attenuation in seawater

$$I_{-}(0,t) = \frac{E_0}{\sqrt{2\pi}\, s_0} \exp\left\{ -t^2 \Big/ 2s_0^2 \right\}$$

$$I_{-}(z',t') = I_{-}(0, t' - z'/c)\, e^{-\int_0^{z'} \Sigma\alpha_{480}\, dz''}$$

$\Sigma\alpha_{480}(z)$ is attenuation (seawater & dye) at laser wavelength

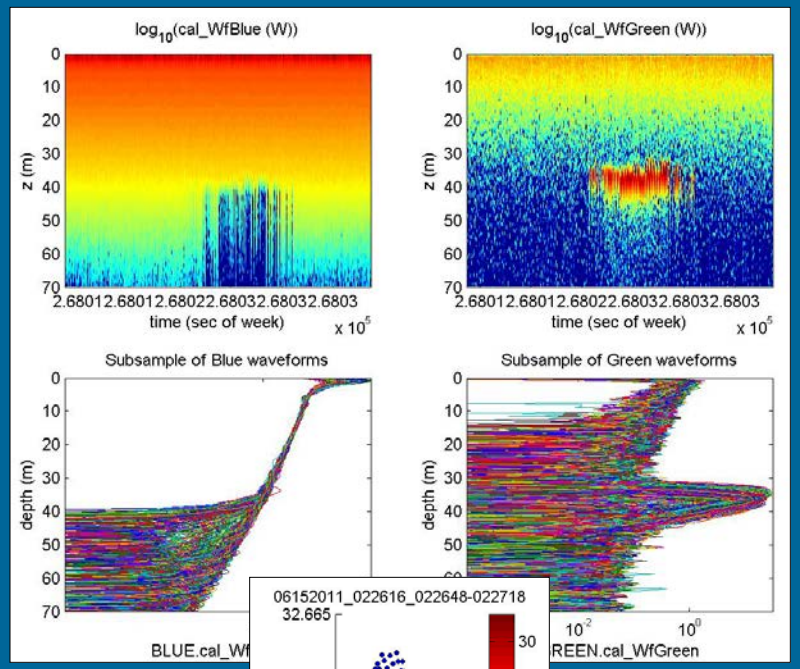
$$I_{b+}(0,t) = E_0 \int_0^{\infty} \frac{1}{\sqrt{2\pi}\, s_0} e^{-\frac{(t-2z'/c)^2}{2s_0^2}} \left(G_s(z')\alpha_{Sb}(z')\, e^{-2\int_0^{z'} \Sigma\alpha_{480}\, dz''} \right) dz'$$

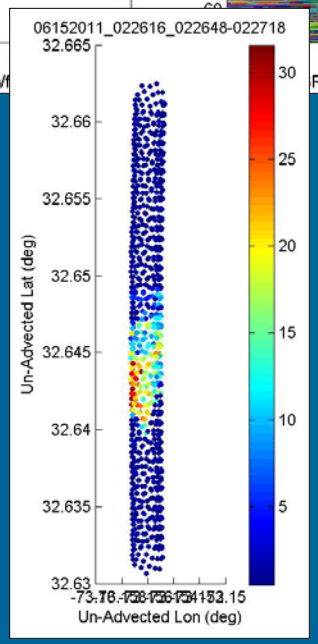
upward flux of fluoresced light @z=0 at all depths z ≥ 0:

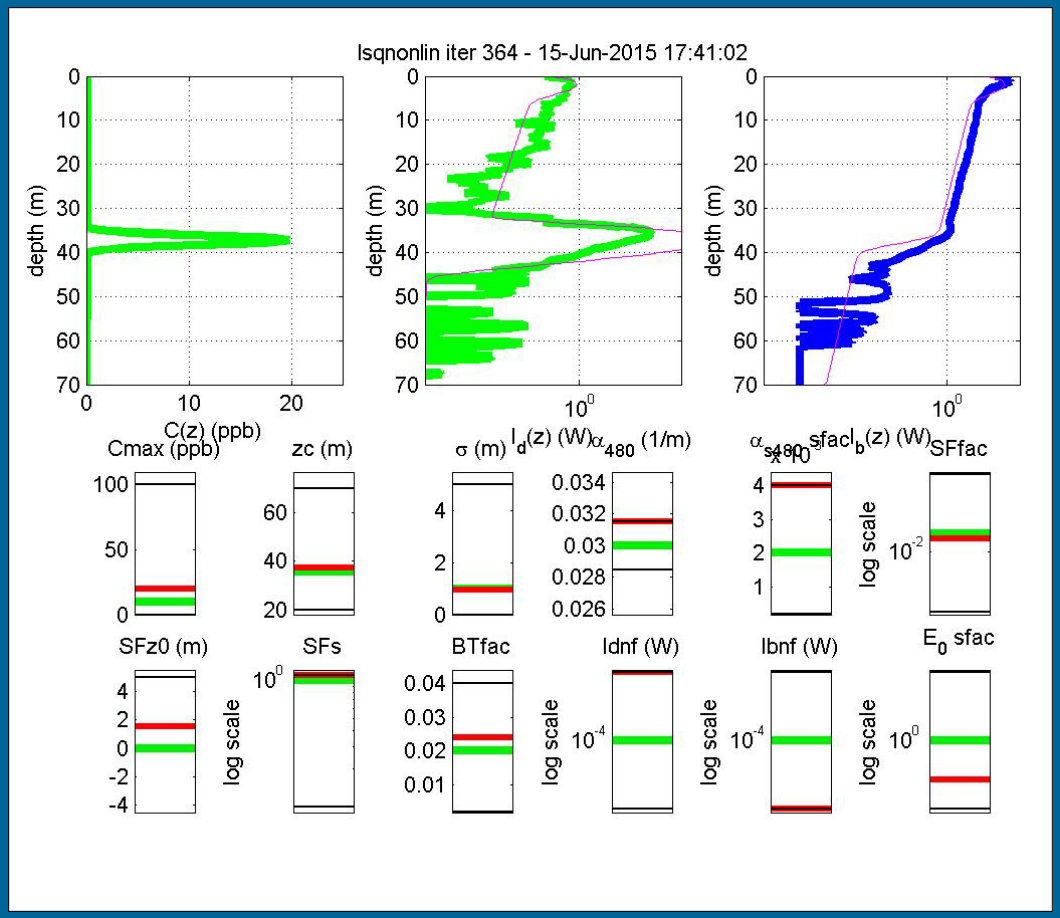
$$I_{+}(0,t) = E_0\, A_d\, QY \int_0^{\infty} \left(\int_{-\infty}^{t-z'/c} \frac{1}{\sqrt{2\pi}\, s_0 \tau} e^{-\frac{(t'-z'/c)^2}{2s_0^2} - \frac{((t-z'/c)-t')}{\tau}} \left(C(z')\, G(z')\, e^{-\int_0^{z'} \Sigma\alpha\, dz''} \right) dt' \right) dz'$$

Sundermeyer

Inverting for Absolute Dye Concentration (ppb)







Sundermeyer

Summary and Conclusions

- Airborne lidar provides unprecedented view of fluorescent dye dispersion in the ocean at scales unavailable to ship-based in situ measurements
- Full waveform inversion reveals 3-D structure in water of dissolved constituents

Ongoing Work

- Explore other lidar applications in coastal waters in tandem with ship-based methods – coordinate mapping/survey activities with academic research
- Explore value-added water-column products using full-waveform lidar data – interested in collaboration / feedback regarding optical inversions and visualization

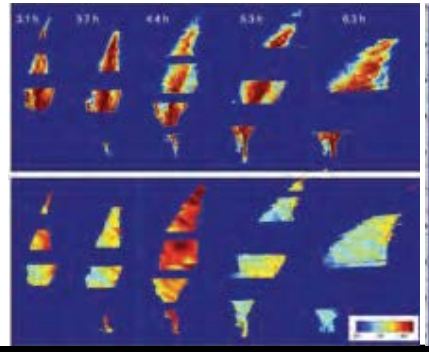
2015 LIDAR Workshop

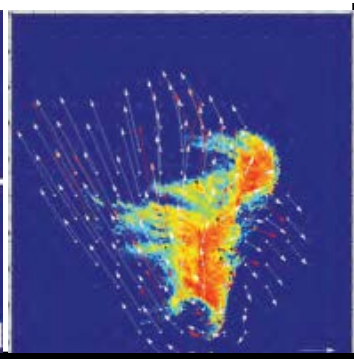
• July 21st - 22nd 2015 • Lowell, MA

Images: DWEL (Dual-Wavelength Echidna Lidar)
NSF MRI Grant # 0923389
PI: A. Strahler (BU), Co-PIs: S. Chakrabarti (UML)
C. Woodcock (BU), T. Cook (UML), C.Schaaf (UMB)

The University of Massachusetts *Experimental Center for Environmental Lidar* (EXCEL) center invites you to the 2015 LIDAR Workshop on July 21–22, 2015. Our goal is to bring together a diverse audience comprising expert users, manufacturers / industry and novice users from academia, industry as well as funding agencies.

Topics include environmental applications in *terrestrial, oceanographic and atmospheric LIDAR*. The workshop includes panel sessions, research presentations, poster displays and a LIDAR short course.

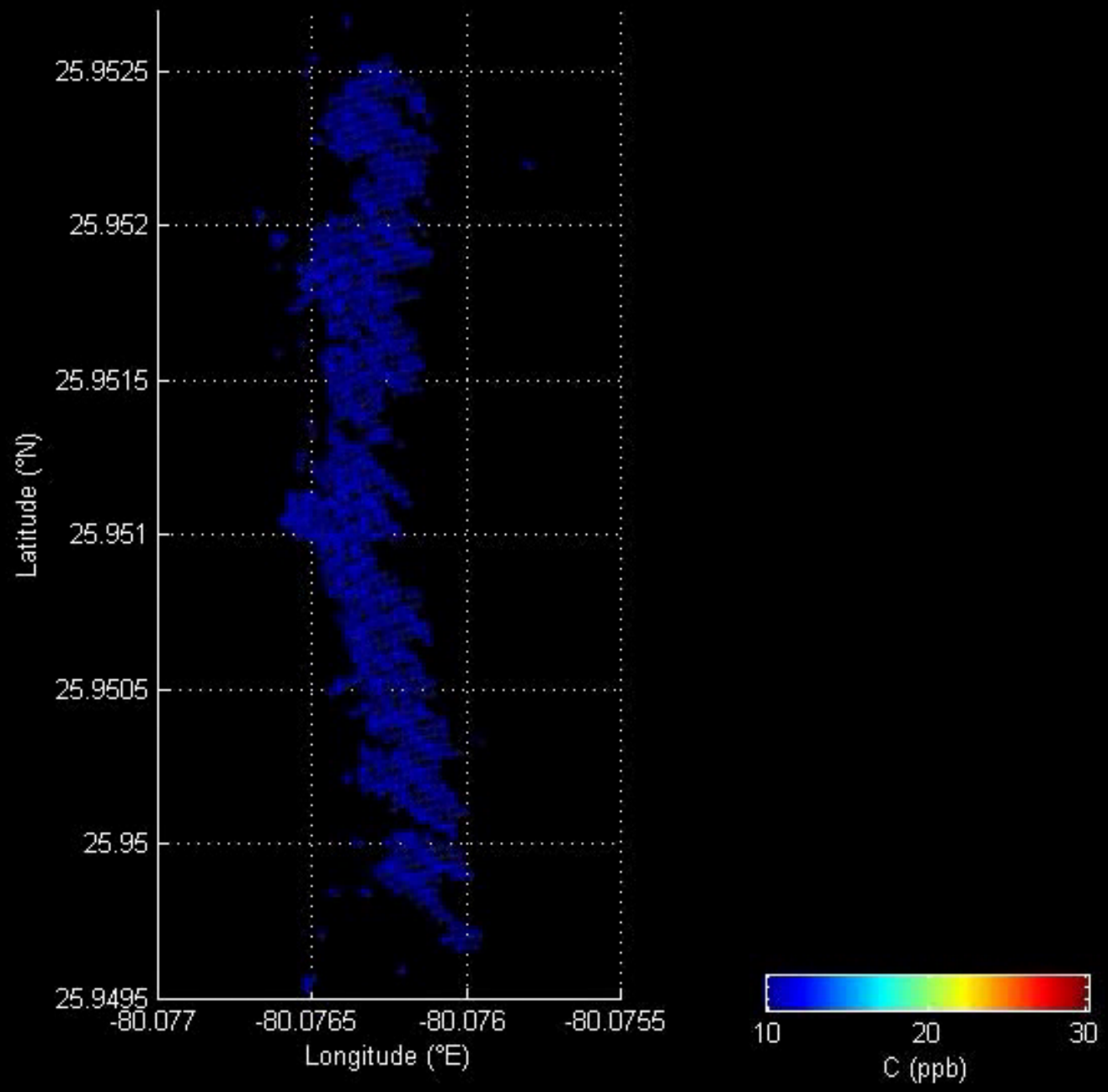




Register at:

http://www.uml.edu/Research/LIDAR-Workshop/

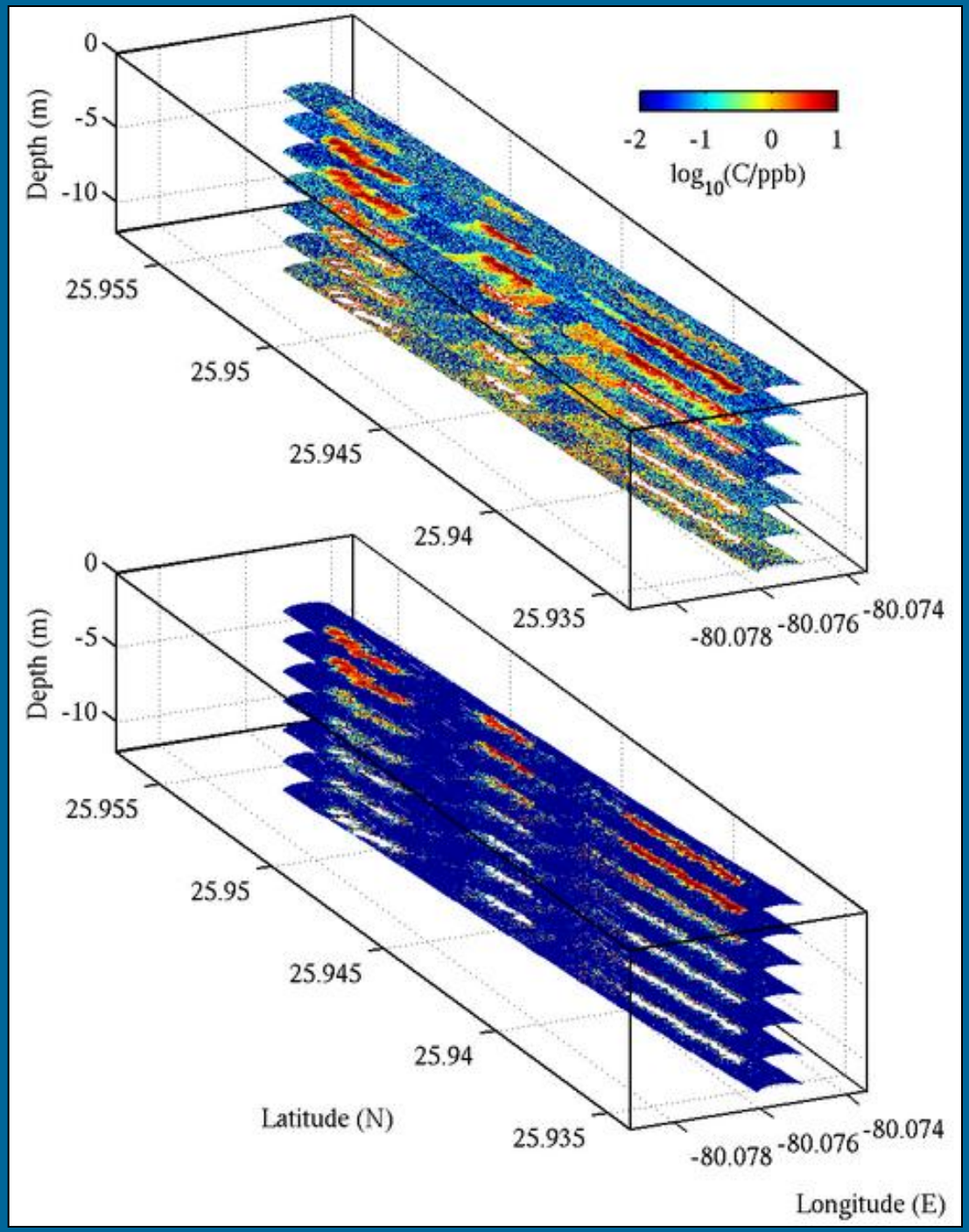
MPG


25.9525
25.952
25.9515
25.951
25.9505
25.95
25.9495
Latitude (°N)
-80.077
-80.0765
-80.076
-80.0755
Longitude (°E)
10
20
30
C (ppb)

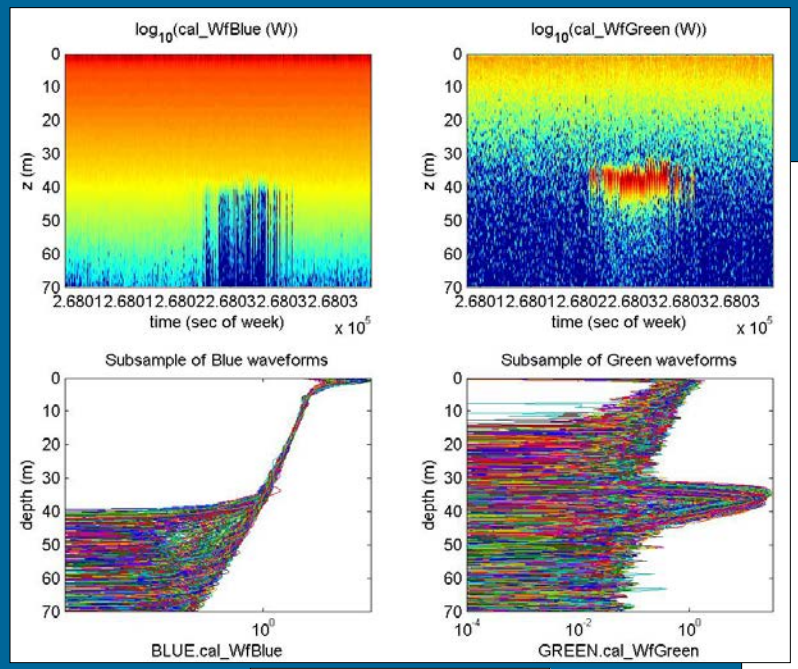
Inversion for Dye Concentration

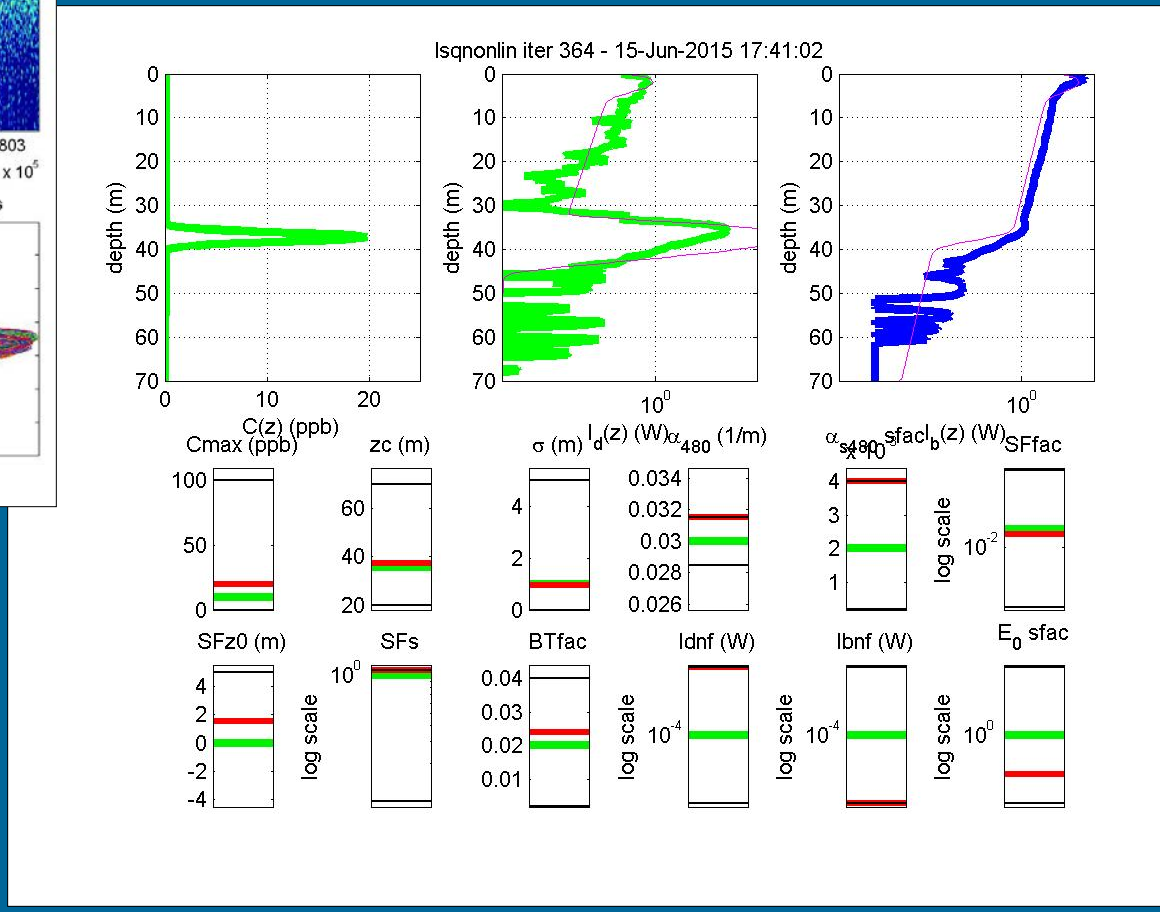
(Terray *et al.*, 2005; Sundermeyer *et al.*, 2007)

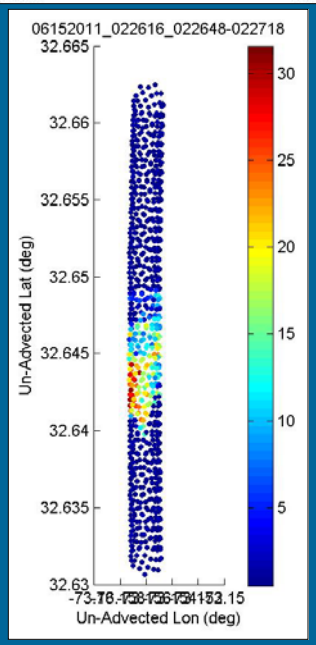
- Green and fluorescence channel inversions show 3D structure of dye streak on scales of meters to 1 km
- Overall detectability for both channels between 0.5–2.0 ppb.
- 20,000 LIDAR profiles per overflight vs. ~200 *in situ* over entire experiment



Inverting for Absolute Dye Concentration (ppb)

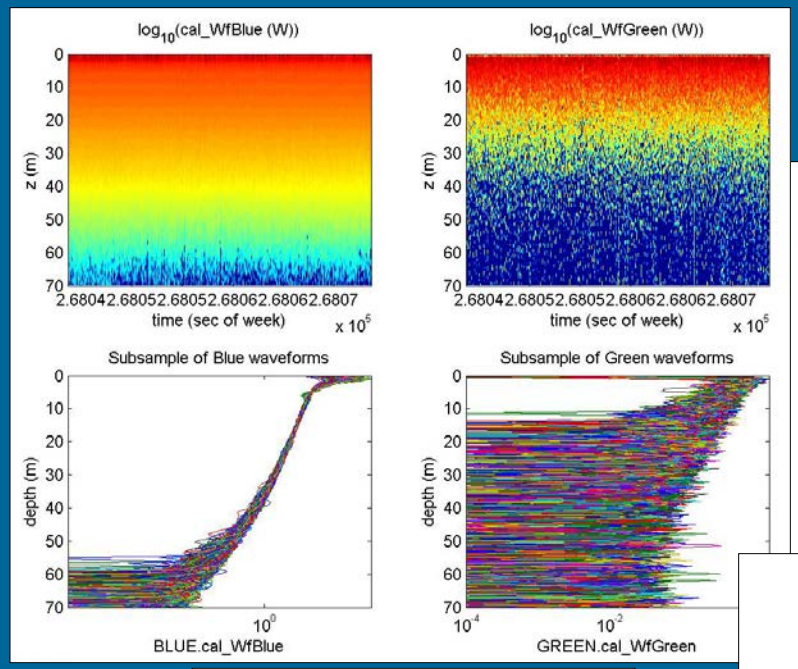


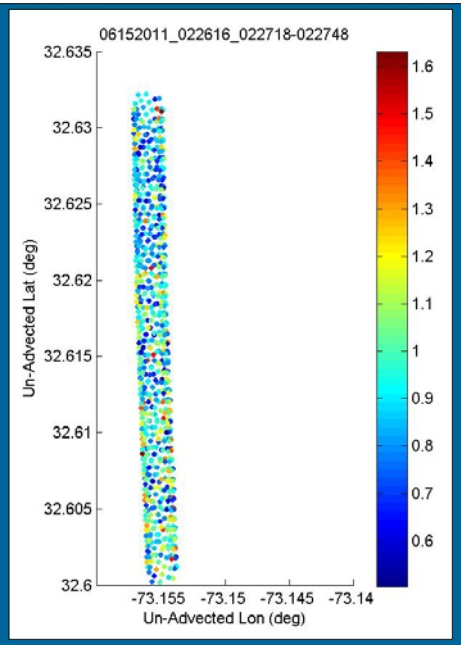


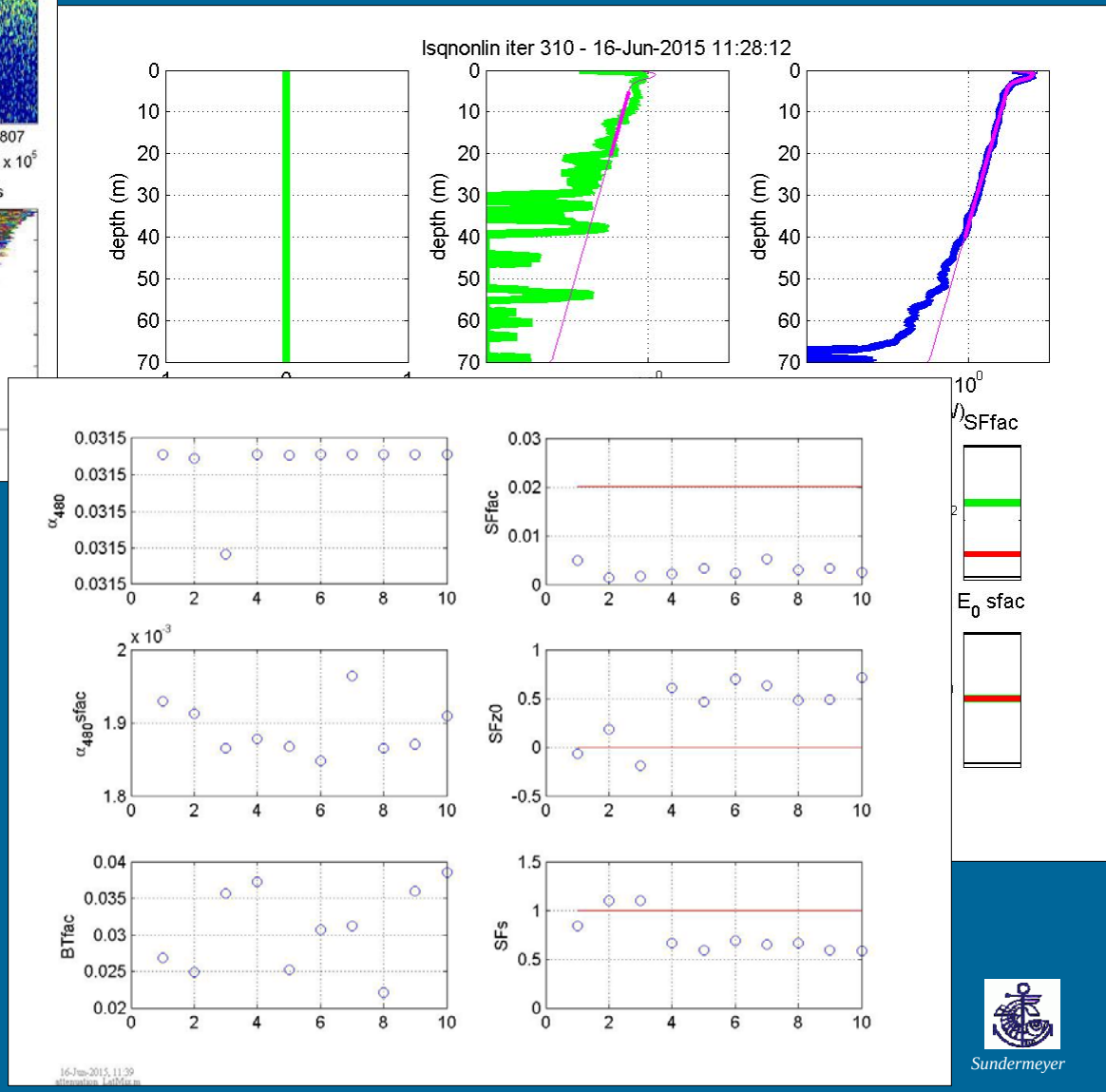


Sundermeyer

Inverting for Absolute Dye Concentration (ppb)

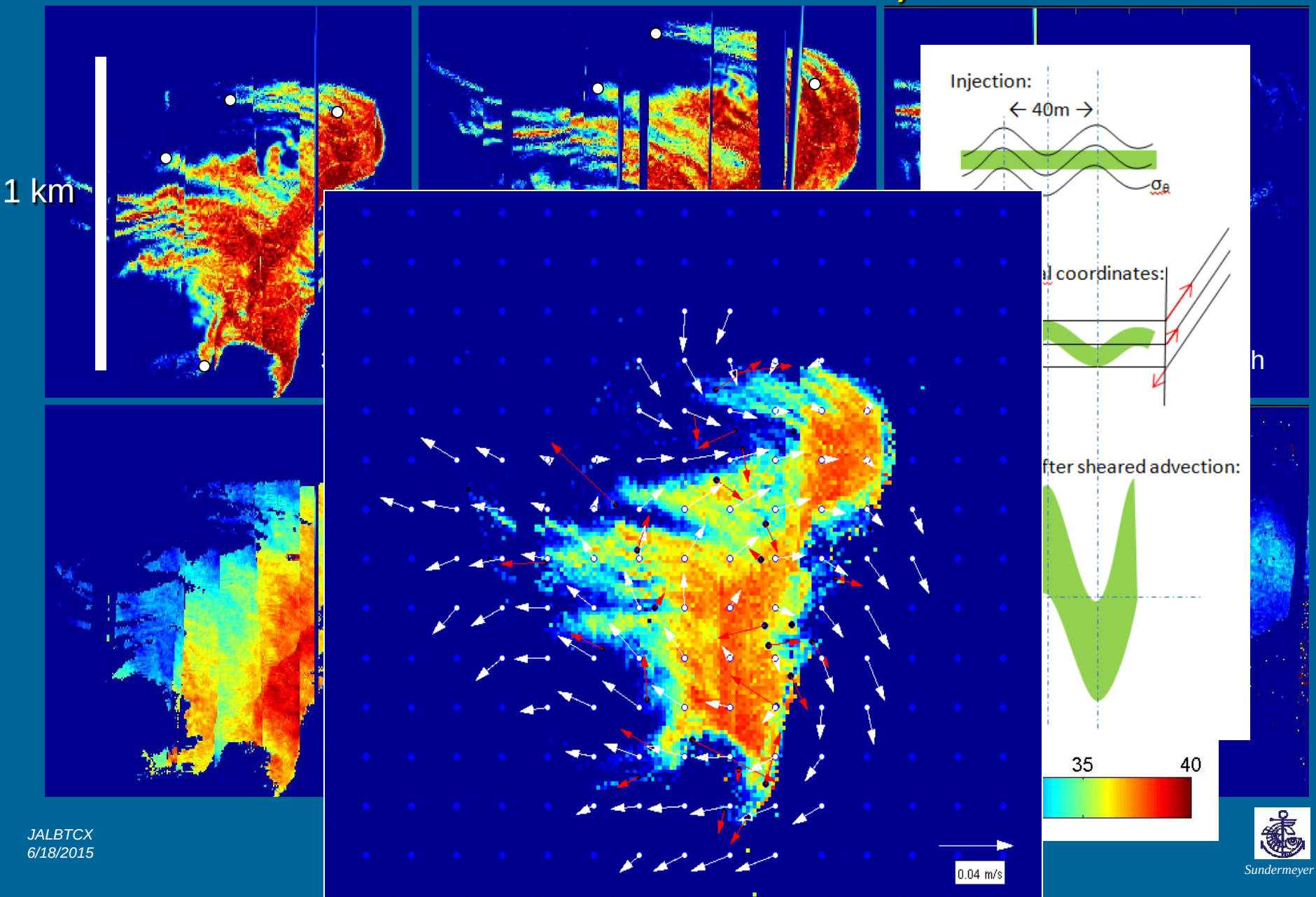






Sundermeyer

ONR LatMix 2011: June 15, Flr5 +

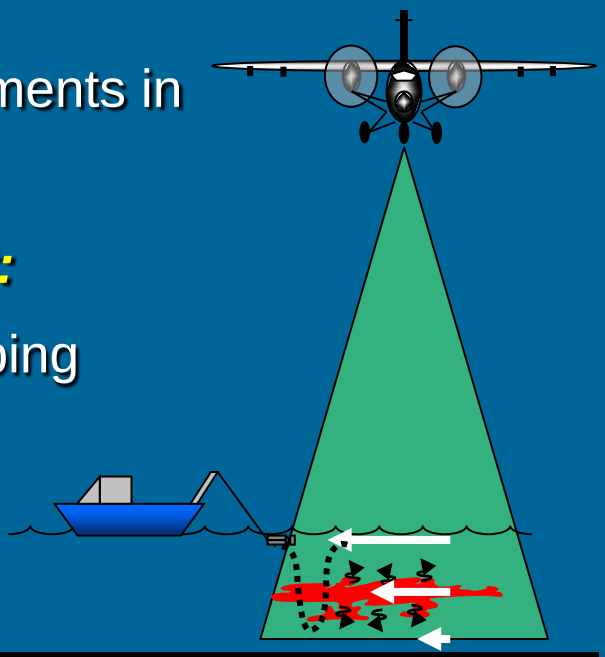


Sundermeyer

Using Airborne LIDAR to Survey Dye Release Experiments

Goal:

- Use airborne LIDAR to survey dye release experiments in upper ocean and pycnocline.

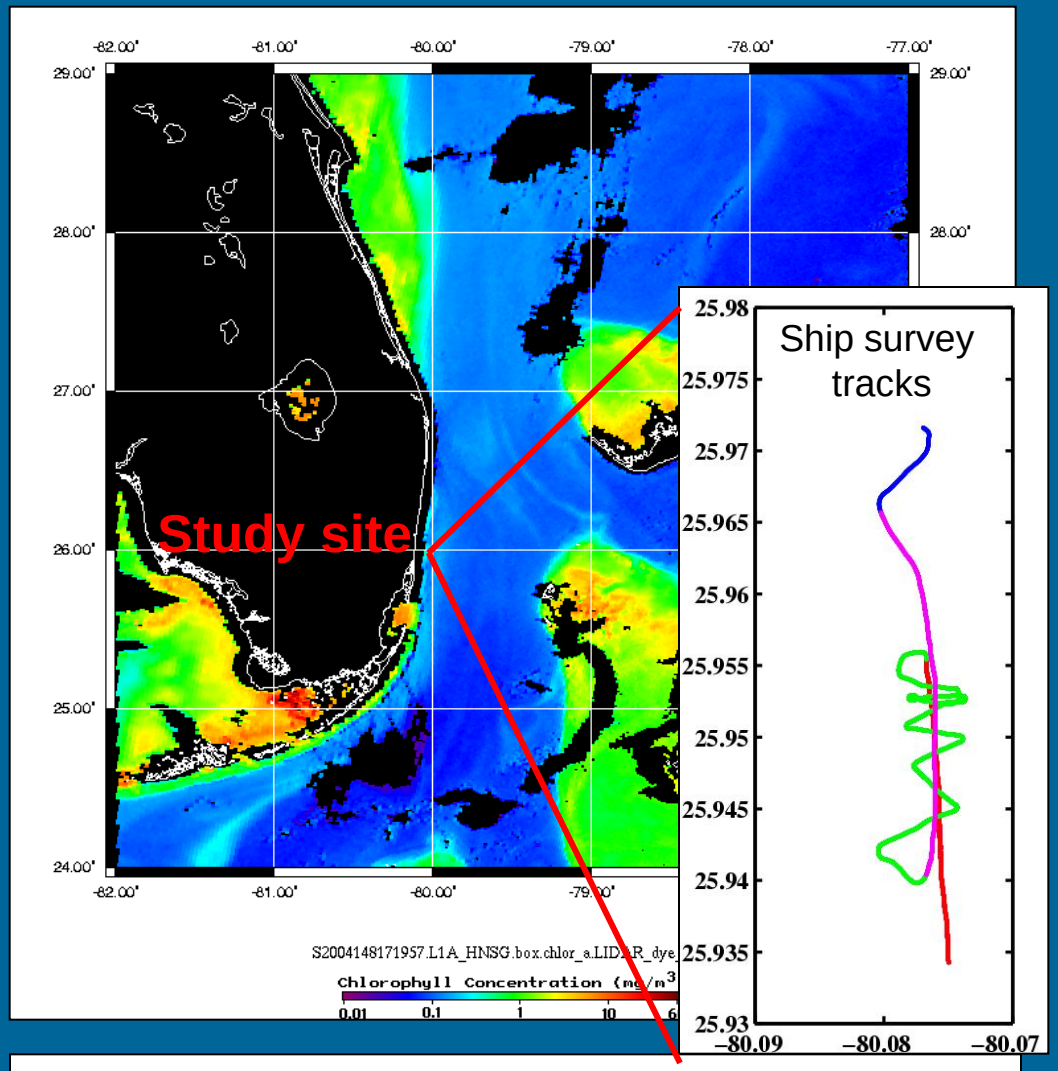
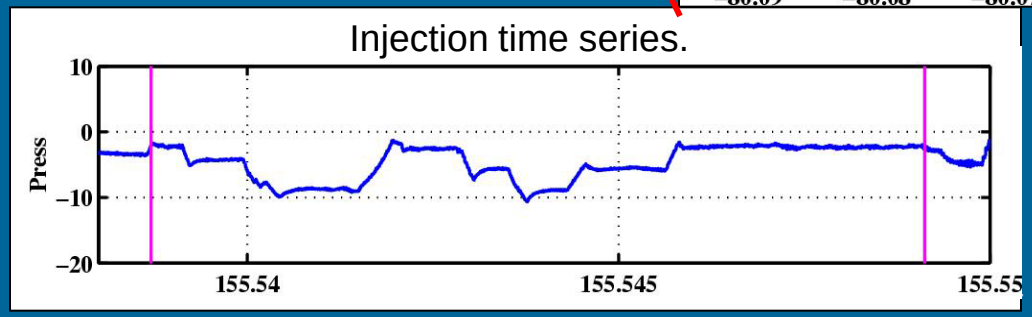


Various downward-looking LIDAR systems exist:

- Bathymetric LIDARs for near-shore coastal mapping
- Custom systems for various applications

SHOALS-1000 LIDAR System Specifications	
Laser	Nd:YAG (532, 1064 nm)
Power	5-6 mJ
Pulse Duration	5 nsec
Pulse rate	1 kHz
Depth penetration	0.1-50 m
Horizontal accuracy	2.5 m
Aircraft speed	125-175 knots
Operating altitude	200-400 m
Swath width	Variable to 0.58 x alt.

2004 Dye LIDAR Proof of Concept

(Sundermeyer et al., 2007)

- Two near-surface releases of 5 kg Rhodamine WT injected in a continuous streak.
- Dye mapped over 1-2 hours using fluorometer & CTD towed from a ship, plus airborne LIDAR.