Ship Generated Internal Waves in SAR Imagery

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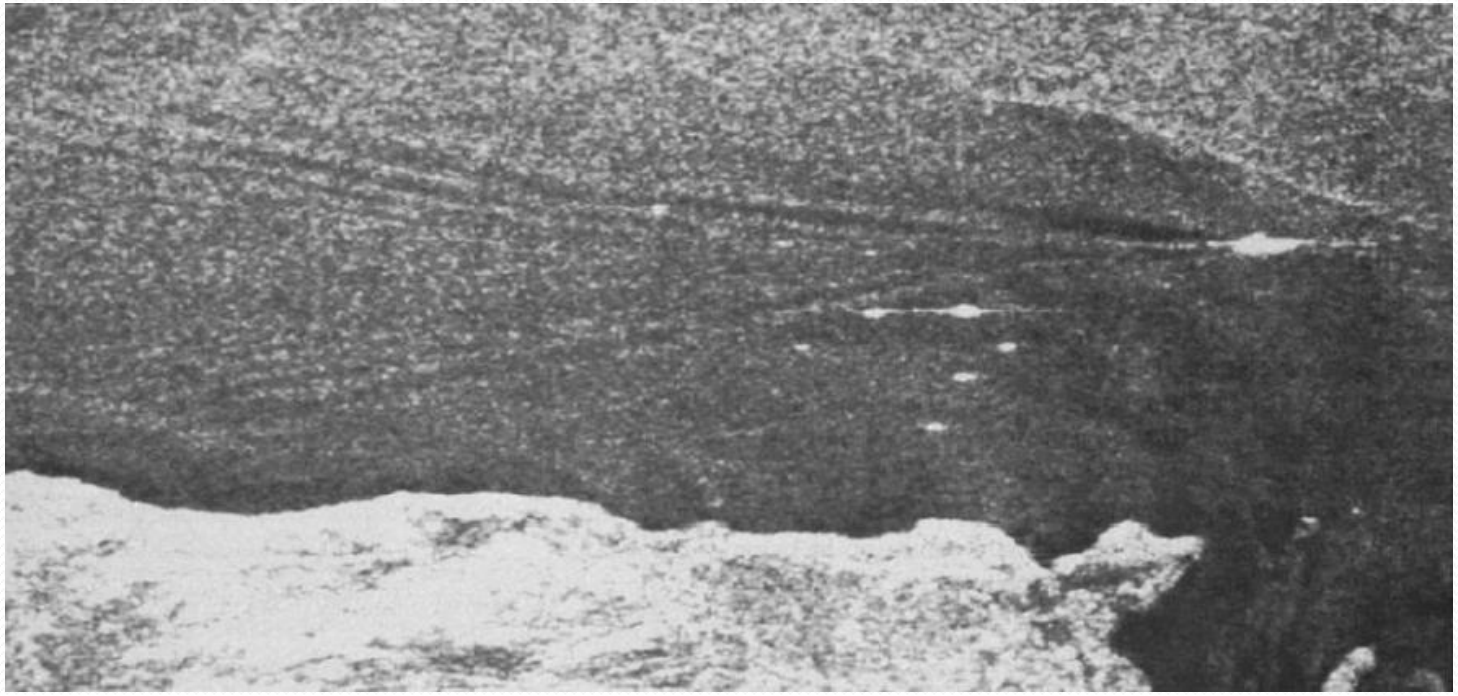
Internal Wave Wake

Sir Tristram wake on Loch Linnhe, Ship speed 2 m/s
L-band airborne radar image. Image length 4 km.



Internal Layers

- Internal layers in the ocean are horizontal stratifications of density:
  - These stratifications can be caused by salinity changes or by temperature changes with depth (or both).
- Discrete model:
  - The density increases abruptly at a certain depth.
  - This is the simplest theoretically.
- Diffuse model:
  - The density increases smoothly with depth.

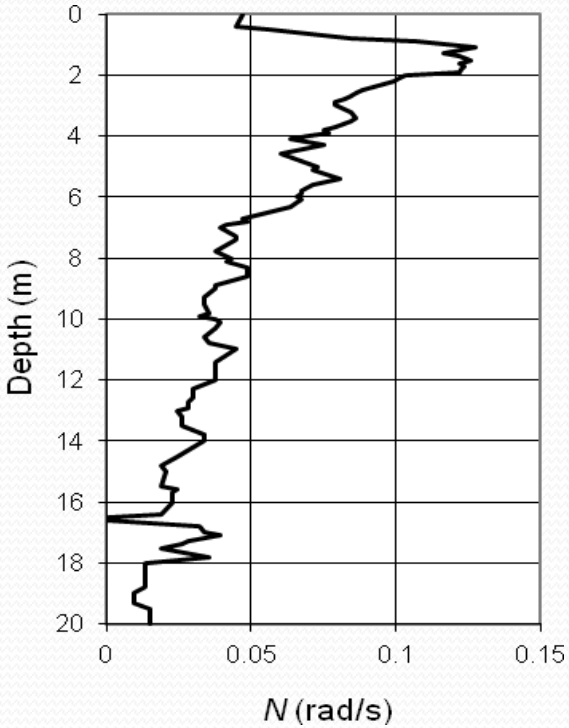
Loch Linnhe Trials

- Several ships
  - Tug, heavy landing ship, fleet oiler.
- Fresh water over sea water provides shallow interface.
- Various airborne SARs.
- Measurements of vertical profiles.
- Estimates of surface velocities: Typically up to 5 cm/s. (See Watson, Chapman and Apel, JGR, **97**(C6), 9689, 1992.)

Loch Linnhe B-V Profile

Brunt-Vaisala Frequency, $N(z)$:
$N^2(z)=(g/\rho)d\rho/dz$

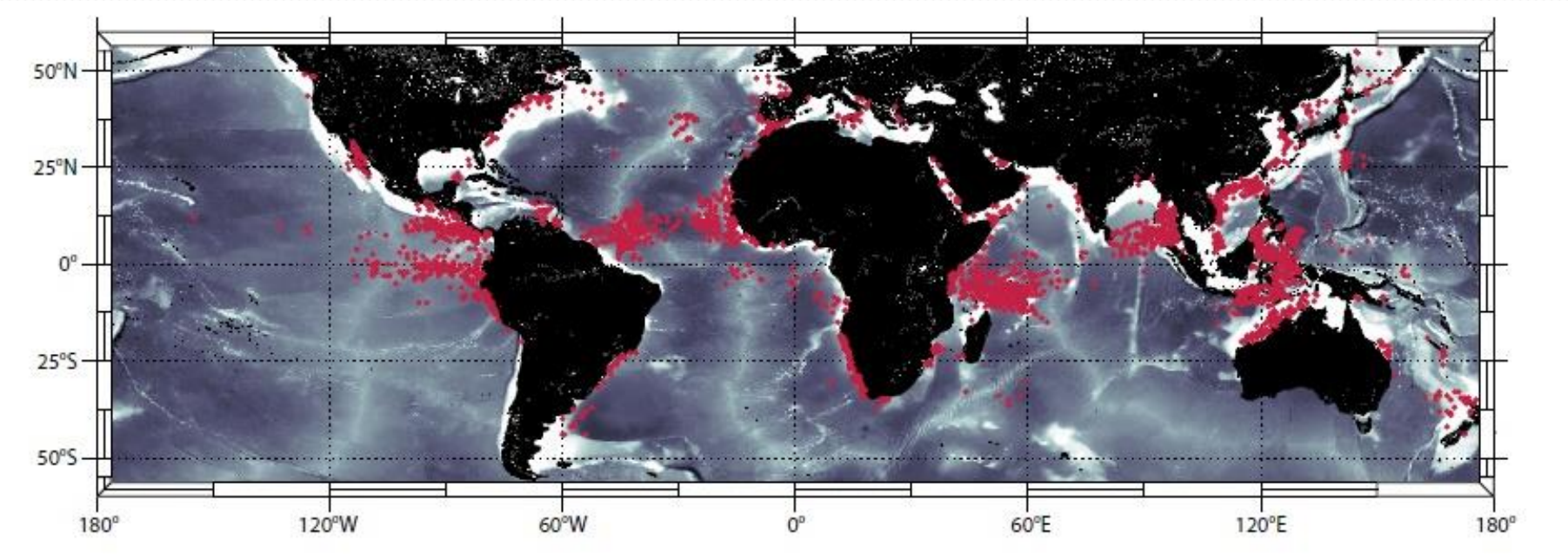
Layers are usually broader & deeper and there is often a mixed layer at the surface (where N = 0), which may be several metres thick.



Internal Waves

- Typically low speed (< 1 m/s).
- Discrete interface or layer
  - Vertical motion resembling ordinary gravity waves on the sea surface.
- Diffuse interface or layer
  - Sinuous waves in which the entire layer oscillates vertically.
  - Varicose waves in which the layer thickness oscillates.
  - Modes in which both occur.
- Natural waves are often non-linear.

Distribution of Natural Internal Waves



From Jackson et al. (2012) using MODIS images from 2002 to 2004

Internal Wave Wake Models

- Steady wakes due to fluid flow around hull.
  - Simulation described here.
- Non-steady wakes:
  - Reflections of ambient waves from the hull.
  - Ship motions, such as heave and pitch.
  - Propeller wakes.

Ship Internal Waves

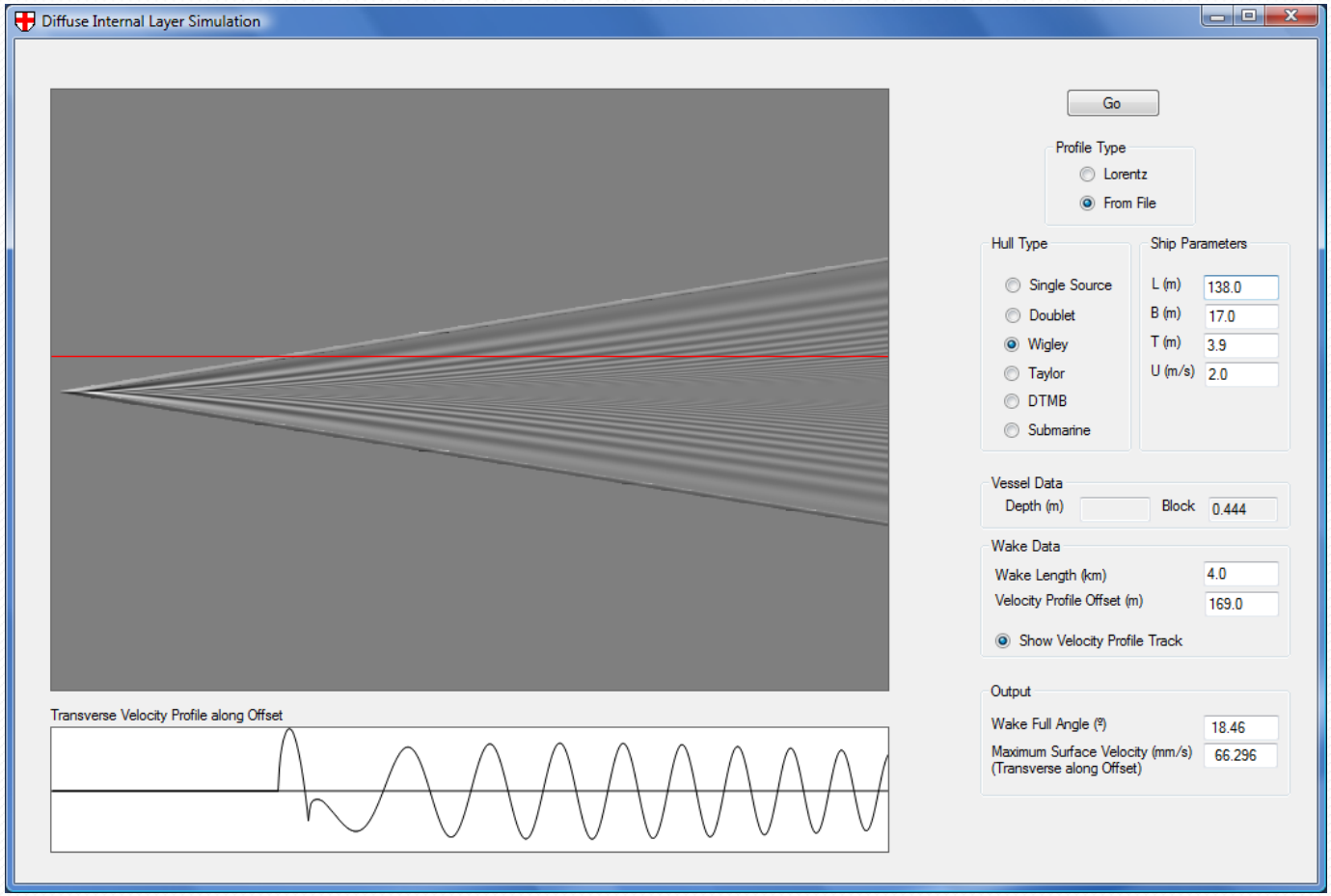
- Theory described in a DRDC contract report: J.K.E. Tunaley, "The theory of internal wave wakes", CR 2012-119, 2012. Also a 2015 report.
- Discrete interface
  - If the ship is mainly above the layer it will push it down as it passes and, if mainly below, it will push the layer up, creating wave trains.
- Diffuse interface
  - For the lowest mode (sinuous), this is the same as the discrete interface.
  - Varicose modes can be present when the ship is in the layer but these are not usually important because they tend not to be strongly excited and their wakes are very narrow.

Ship Models

- Single source.
- Doublet.
- Wigley: A simple parabolic hull (c.f. Canoe).
- Taylor: Modeled on a twin screw cruiser.
- David Taylor Model Basin (DTMB) Series 60: Single screw merchant hull.
- Can choose hull block coefficient for Taylor & DTMB.
- Note: In simulations, there is usually negligible difference between Wigley, Taylor and DTMB hulls.

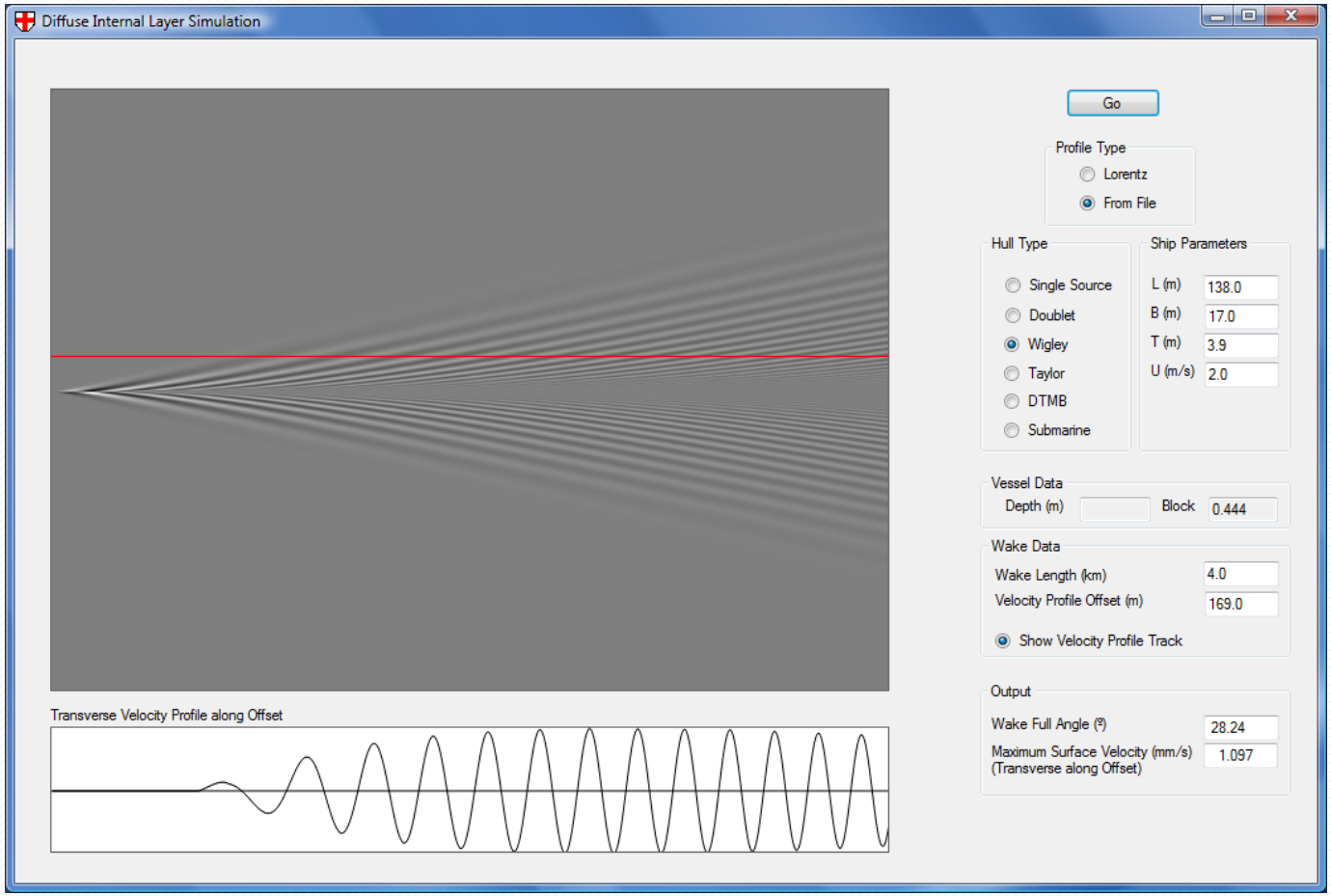
Program

Sir Tristram parameters on Loch Linnhe



Effect of Mixed Surface Layers

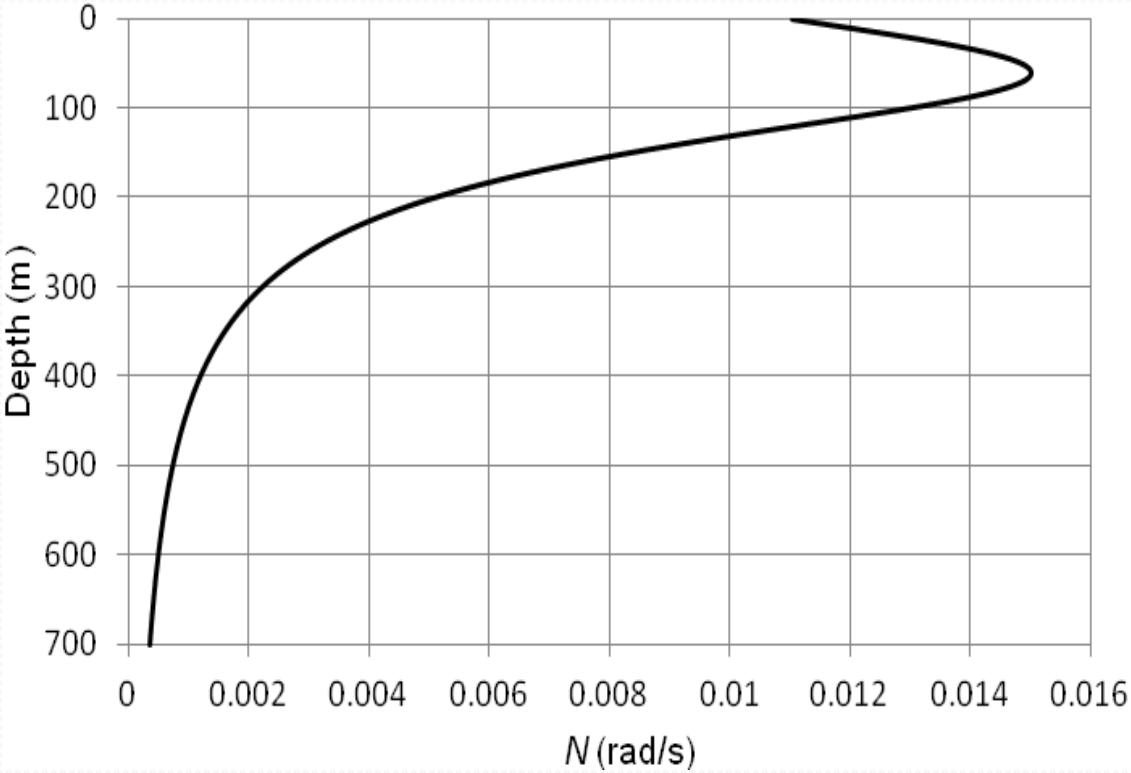
Effect of a 5 m mixed layer at the surface.



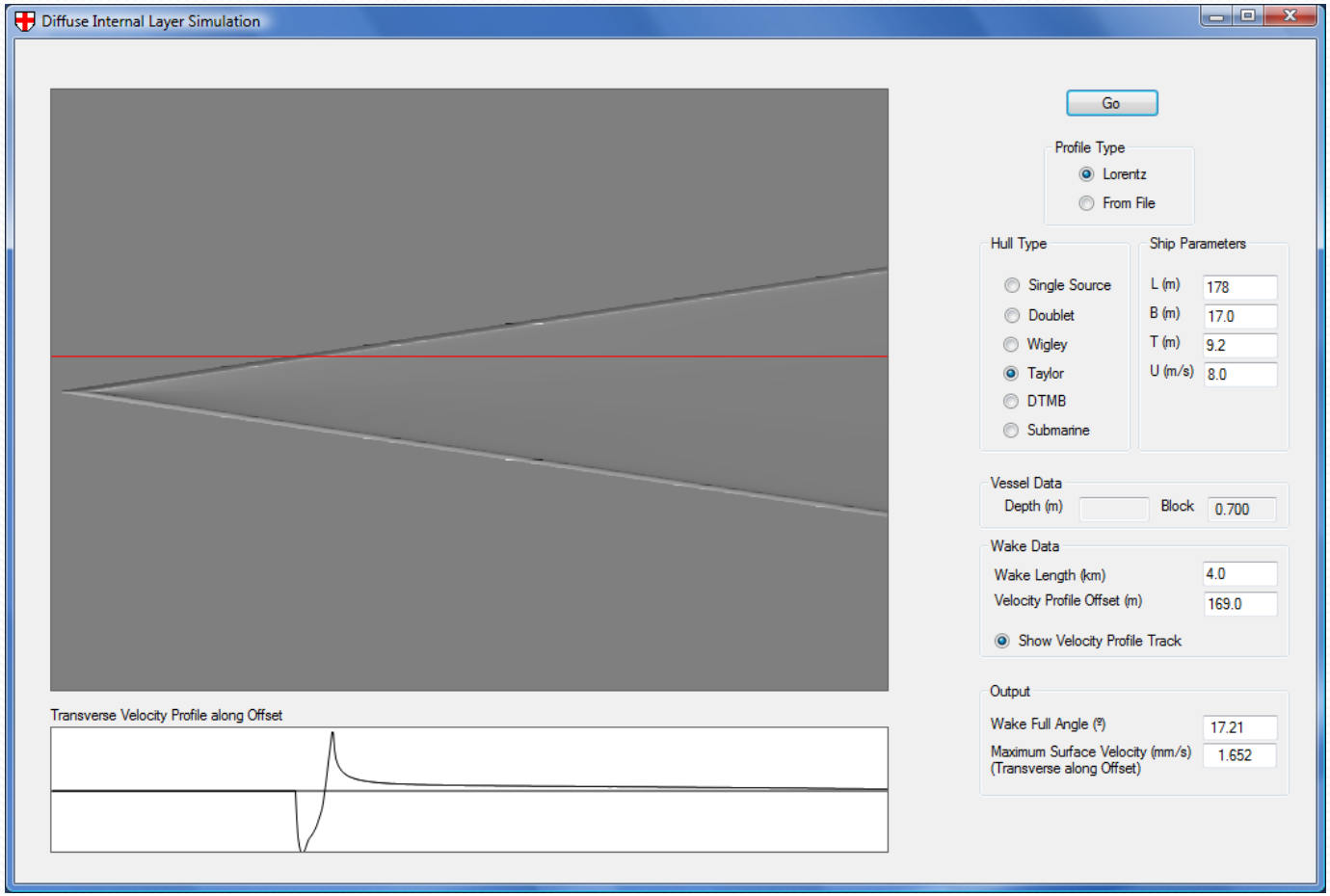
Effect of Mixed Surface Layer

- As depth of mixed layer increases:
  - Wake angle tends to increase because layer is deeper.
  - Maximum horizontal surface velocity decreases & wake becomes fainter.

Gibraltar Profile



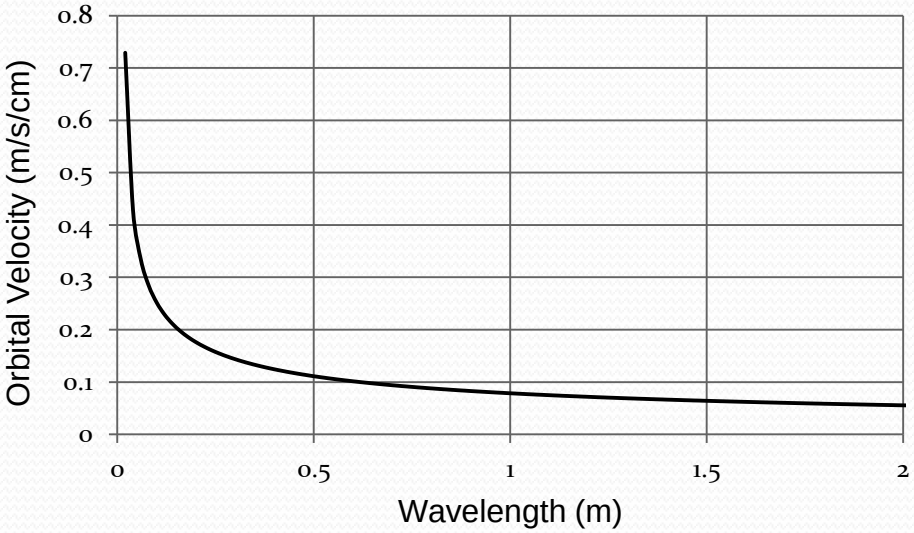
Wake in Gibraltar Profile



SAR Parameters

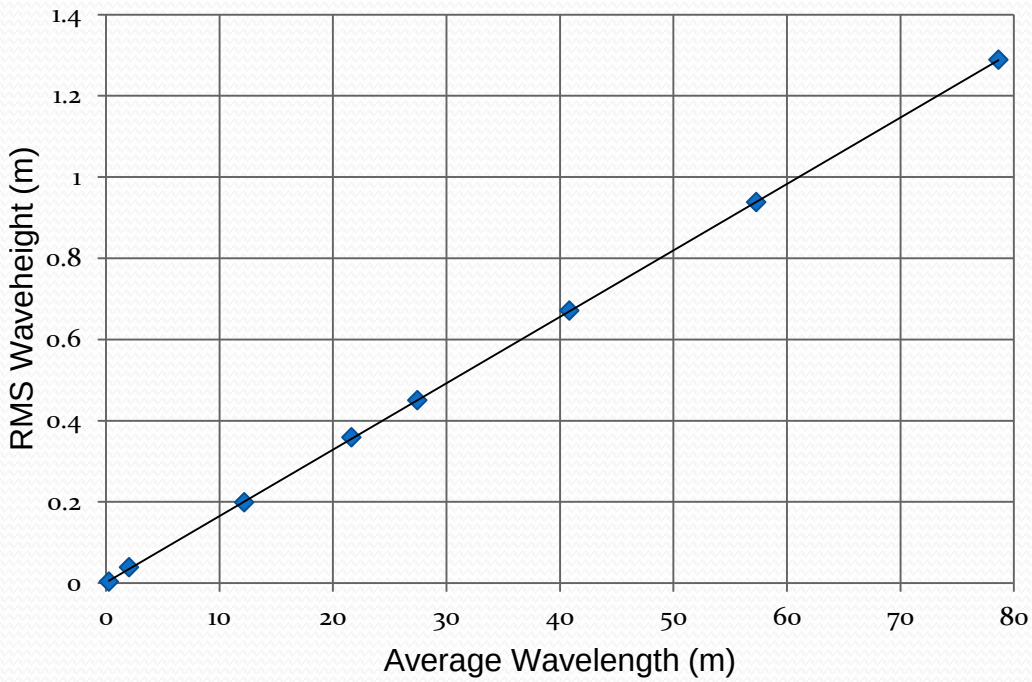
- Note: Wake pattern moves with ship.
- Resolution: For high resolution SAR consider
  - Synthetic aperture time (small for airborne radar).
  - Range migration (but wave speeds small for IWs).
- Velocity bunching (ratio: Slant Range/Platform Velocity).
  - Airborne (about 50 s): Space-borne (about 200 s).
  - Affects cross-range smearing due to ambient wave motion.
- Frequency
  - Affects Bragg wavelength, which affects wave damping.

Ocean Wave Surface Velocities



Wave orbital velocities per cm. amplitude for deep water (surface tension included).

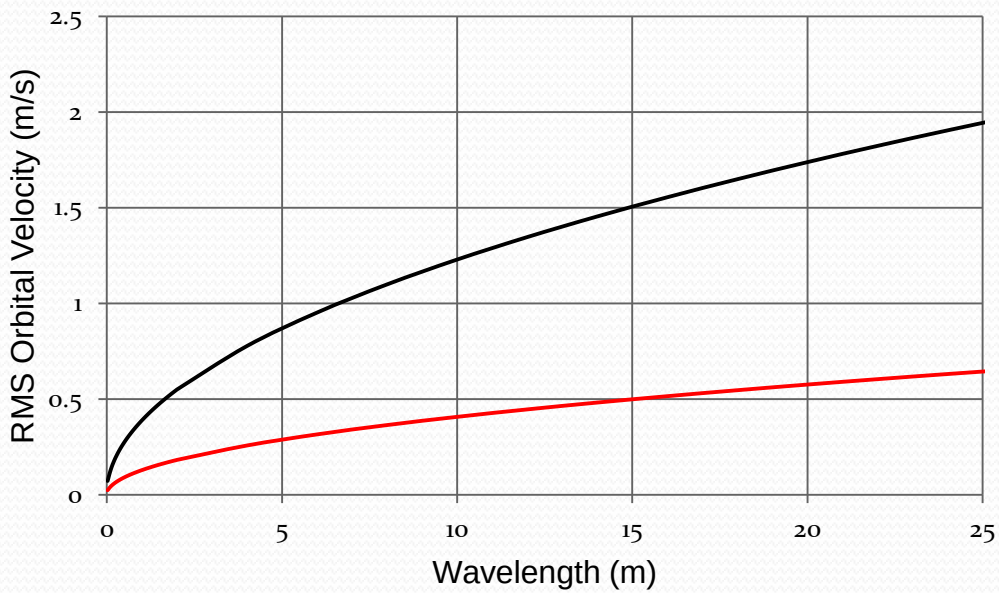
Seastate Data



Data originally from Moskowitz and Pearson (1964)

$\sigma = 0.0164\lambda$

Breaking Wave Limitations



Based on Lighthill limit $a_{max} = 0.07\lambda$: Black.
Pierson-Moskowitz: Red.
$\lambda_{SS_1} = 2m$; $\lambda_{SS_2} = 12m$; $\lambda_{SS_3} = 22m$.
Note: To Compare with Doppler Bandwidth - double.

Conclusions

- Using RADARSAT-2, say, and assuming surface velocities of at least 1 cm/s are required for detection, internal wave wakes are on the threshold of detectability or below it.
- Very high azimuthal resolution is not necessarily advantageous due to smearing associated with velocity bunching.
- Observed wakes may be more likely at low radar frequencies, such as L-band and P-band, because Bragg waves are lightly damped. However, synthetic aperture times may be increased.