SAR and IfSAR observational concepts for marine debris mapping and oceanic monitoring

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Outline

- An overview of radar interferometry and mapping
  - Surface water velocity mapping techniques
  - Water and terrain elevation mapping techniques
- Near-surface current profiling
- “Analogous” observations of sea-ice using Ka-band airborne ifSAR
  - Exploitation of surface return and inteferometric properties to detect debris or debris fields
- Platform options and scaled scenarios/concepts
  - Shore-based/Ship-based (sensor concept)
  - Suborbital (piloted and unpiloted)
  - Satellite
- A proof-of-concept demonstration

Strengths of Radar Mapping

- Active system (works day or night)
- Not affected by cloud cover or haze if $\lambda > 2$ cm (Ku-band or lower)
- Unaffected by rain $\lambda > 5$ cm (C-band or lower)

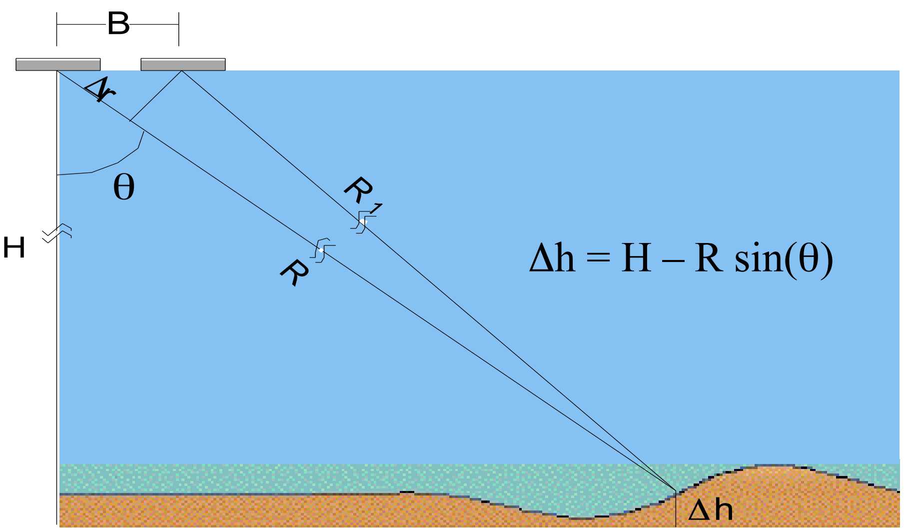
Applicable at multiple scales->multiple platforms:

1. Ground/shore-based systems for continuous coverage
2. Ship-based systems for opportunistic data along shipping routes *and* situational awareness/hazard avoidance
3. Airborne/Suborbital deployable systems for targeted/extended coverage
4. Satellite based systems for large-scale coverage

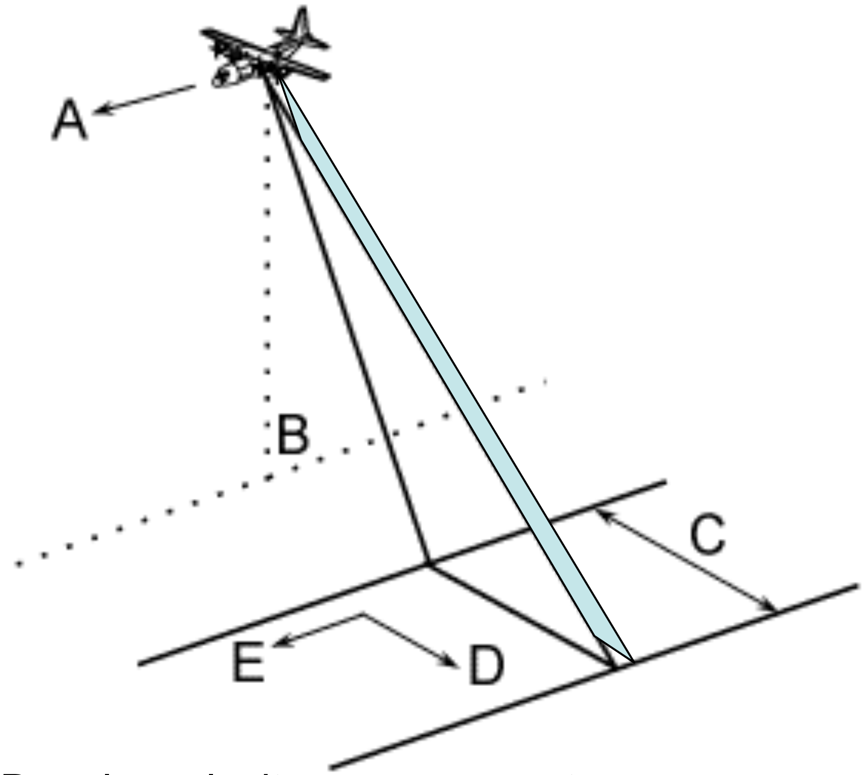
All are relevant and complementary given the temporal, spatial *and technology* spectrum of observations needed to adequately bound dispersion and forecasting models.

Interferometry for Elevation and Velocity Mapping

- In addition to backscatter strength, addition of displaced receivers in elevation and/ or time can enable measurements of surface height and/or velocity respectively



range



- Phase difference between two complex returns is related to the path difference (Δr) to a point on the surface:

  $$\Phi = 2\pi\Delta r / \lambda = 2\pi B \sin(\theta)$$

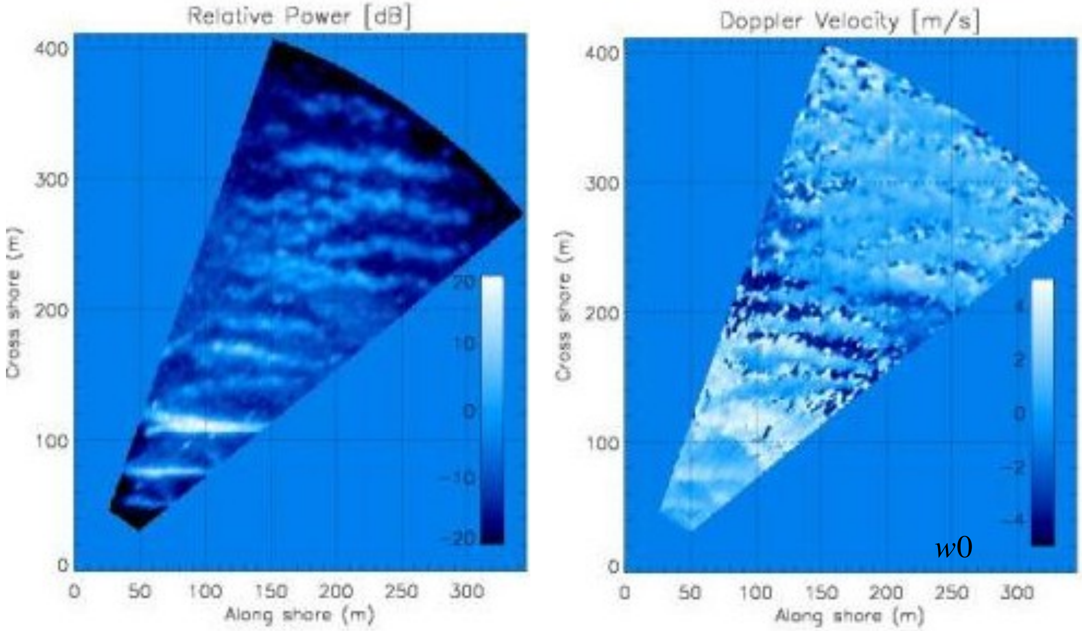
- Incidence angle θ is determined from Φ.
- Elevation (Δh) can be retrieved from :

  $$\Delta h = H - R\sin(\theta)$$

Doppler velocity measurements are derived from the phase of the covariance the backscattered field separated by a short time-lag, τ:

$$V = \lambda\,\Phi / 2\pi \sin(\theta)\tau$$

Upper Surface Current Profiles



When no current is present linear gravity waves follow the dispersion relation:

$$\omega_0 = \mathrm{sqrt}(g|\mathbf{k}|\tanh(|\mathbf{k}|d)$$

This is modified in the presence of current:

$$\omega = \omega_0 + \mathbf{U.k}$$

We assume the vertical current structure [1]:

$$U(k) = 2k \int_{-d}^{o} U(z) e^{2kz} \, dz,$$

Then U(k) approximates the current at mean depth:

$$d_m \sim 1/2k = \lambda_0/2pi$$

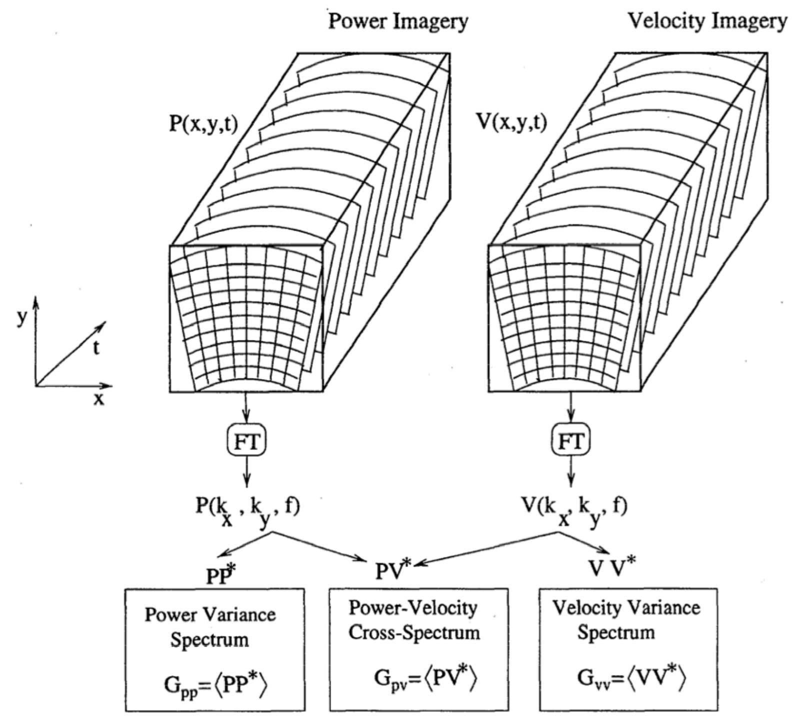


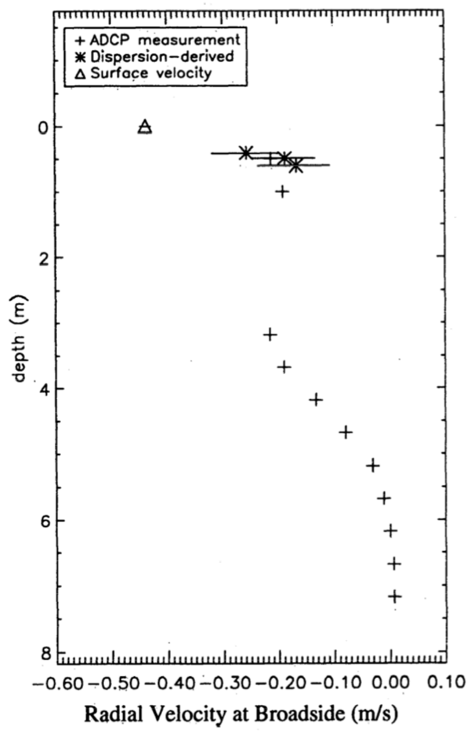
Figure 9. Method by which FOPAIR imagery is transformed into wavenumber/frequency space by applying a three-dimensional Fourier transform applied to a time series of power (P) and velocity (V) imagery. Several spectral products are calculated from the transformed imagery: the power variance spectrum G_{pp}, the power-velocity cross spectrum G_{pv}, and the velocity variance spectrum G_{vv}.

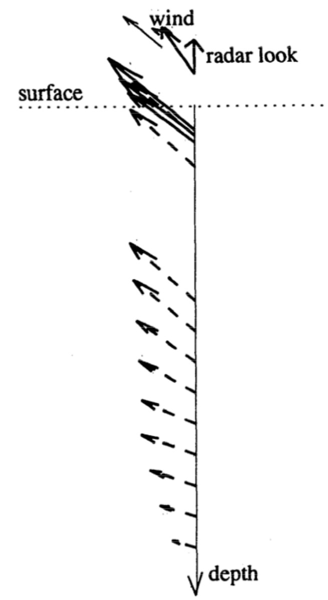
[1] Stewart, R. H., and J. W. Joy, HF radio measurements of surface currents, *Deep Sea Res. Oceanogr. Abstr.*, *21*, 1039–1049, 1974.

Example Vertical Profile compared with ADCP

Table 3. Vertical Profile of Currents for the Downwind, Down-Current Case Shown in Figure 12

Depth, m	Sensor	$\lvert\mathbf{U}\rvert$, m s^{-1}	$\angle\mathbf{U}$, °T	U_r, m s^{-1}
0	FOPAIR	···	···	−0.44 ± 0.01
0.41	FOPAIR	0.34 ± 0.05	001 ± 6	−0.26 ± 0.06
0.49	FOPAIR	0.27 ± 0.05	356 ± 7	−0.19 ± 0.06
0.50	ADCP	0.27	004	−0.21
0.61	FOPAIR	0.24 ± 0.06	356 ± 8	−0.17 ± 0.07
1.0	ADCP	0.25	002	−0.19
3.18	ADCP	0.27	004	−0.21
3.68	ADCP	0.25	002	−0.19
4.18	ADCP	0.20	353	−0.13
4.68	ADCP	0.17	340	−0.08
5.18	ADCP	0.14	324	−0.03
5.68	ADCP	0.14	317	−0.01
6.18	ADCP	0.12	312	0.00
6.68	ADCP	0.10	308	0.01
7.18	ADCP	0.06	305	0.01





Moller D., S.J. Frasier, D.L. Porter, R.E. McIntosh, "Radar-derived interferometric surface currents and their relationship to subsurface current structure", *Journal of Geophysical Research- Oceans,* Vol. 103(C6), 12,839-12,852, 1998.

Example Vertical Profile: Wind Oblique to Current

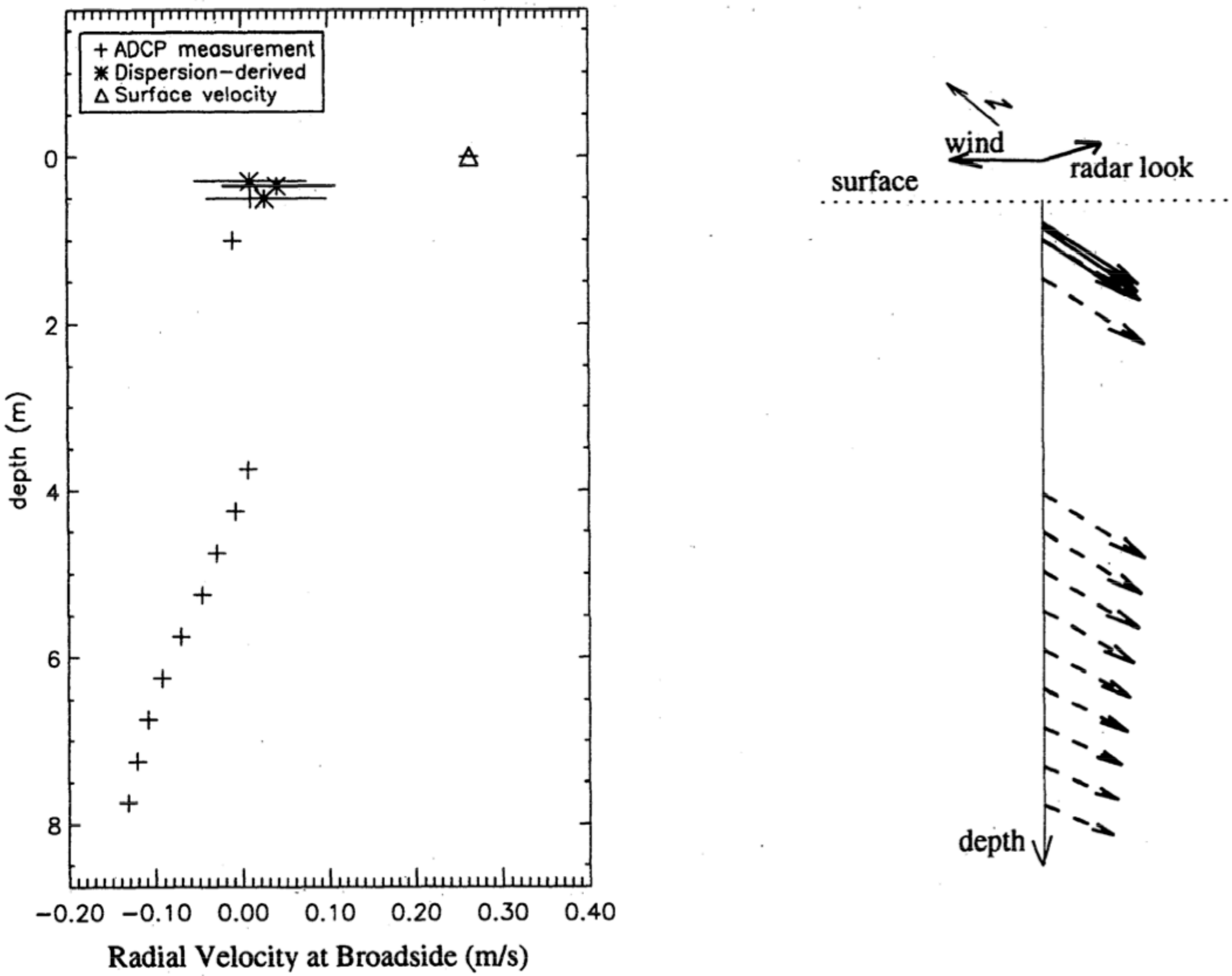
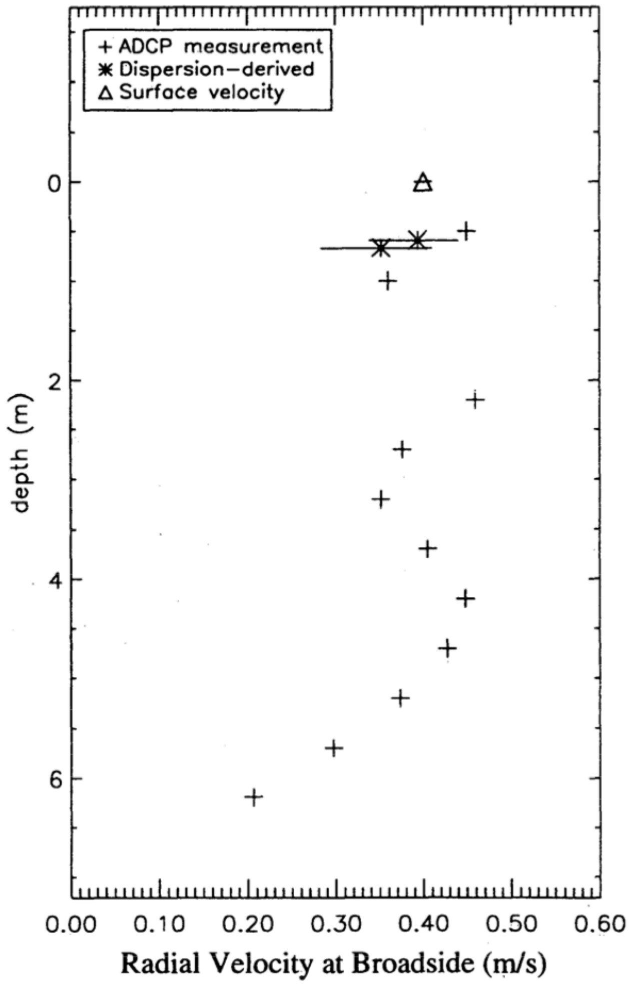
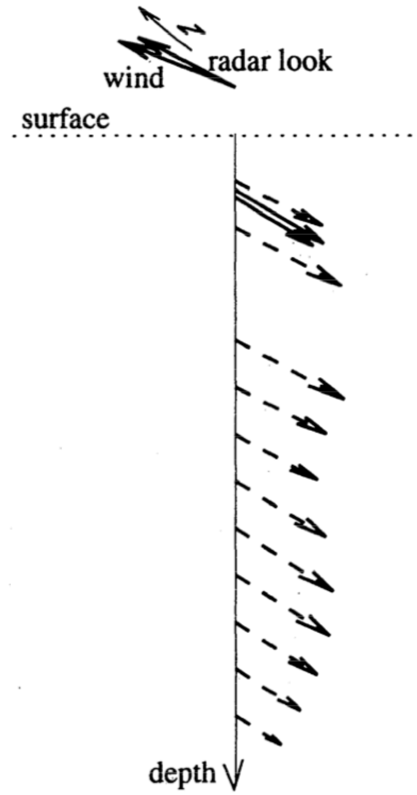


Figure 11. Vertical profile of current structure when the radar is oriented upwind and cross current. (left) Current evolution in the radar line-of-sight direction. (right) The series of vectors show the evolution of the current with depth.

Example Vertical Profile: Wind opposite current

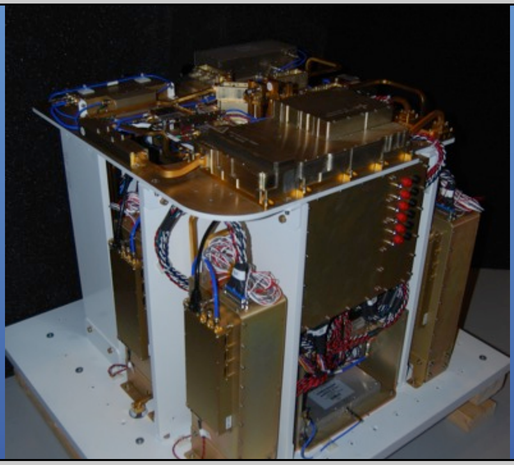




- Could apply similar technique to trace the upper current profile (meters) to surface.
- Limitation on depth is spatial extent to adequately sample the gravity wave spectrum to estimate distortion at depth
- Could customize design for stationary or slowly moving platforms to profile near-surface

Airborne Radar for Debris Mapping

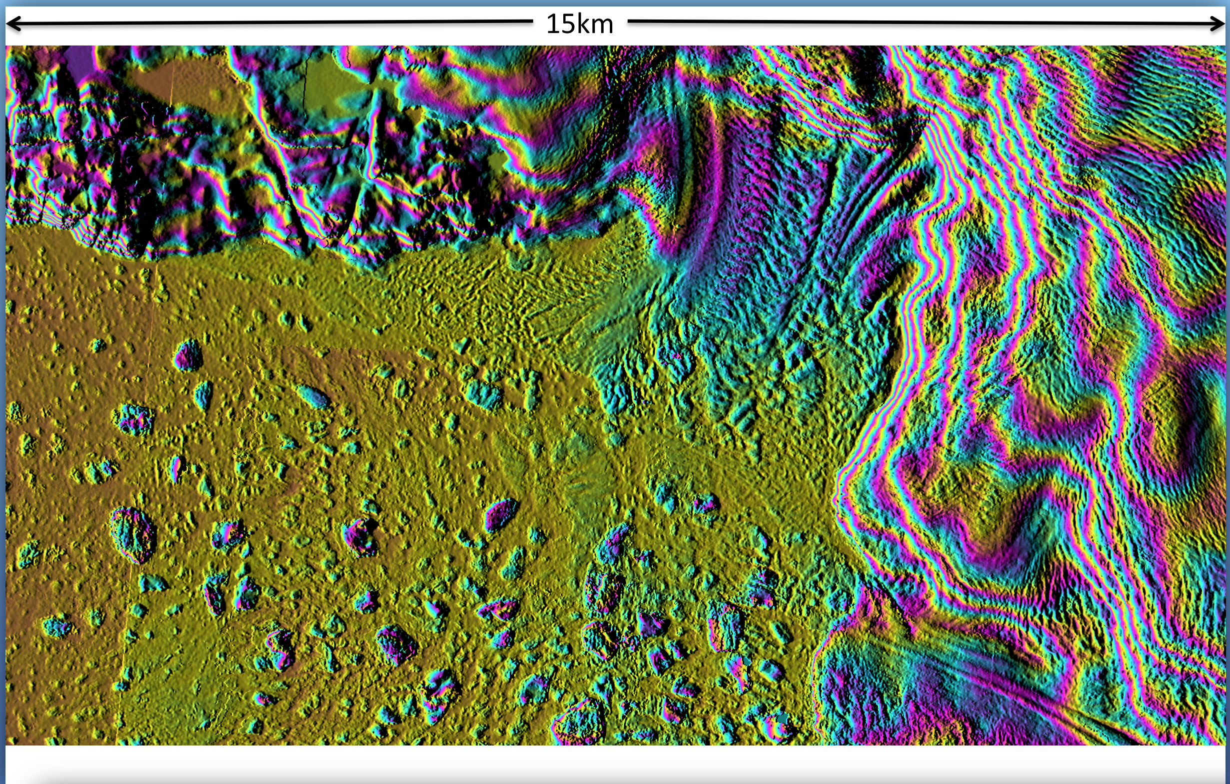
GLISTIN-A Ka-band antennas installed on the NASA GIII configured for single-pass interferometry



Compact six-channel SAR interferometer developed for SWOT calibration/validation

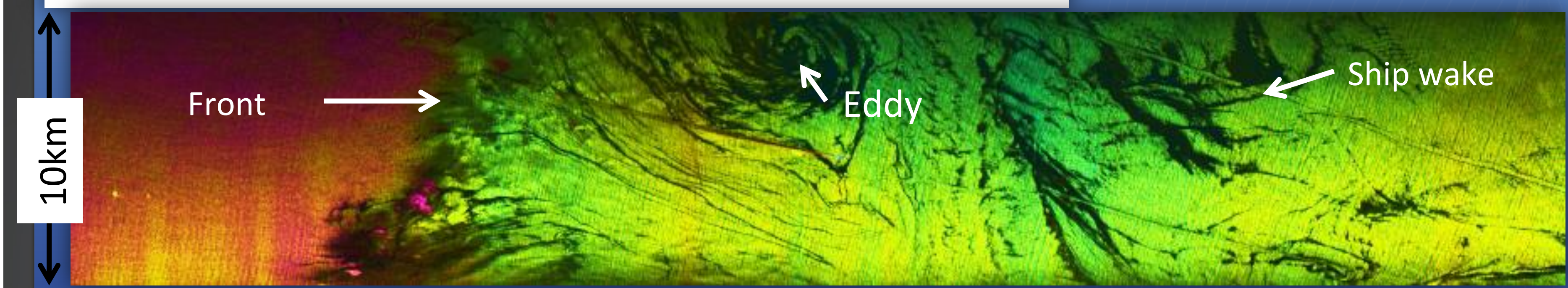
- Imaging 3-D radar capable of 10-12km swaths for surveillance
- Operation independent of daylight or cloud cover
- Targeted high-resolution debris maps
  - Locations
  - Size distribution (surfaced)
  - Height (above surface)
  - Drift velocities of debris relative to the ocean (windage?)
- Improved tracking efficiency by coupled observations and modeling

Sample Survey Products



- Left image: outflow from Jakobshavn glacier, Greenland. Height is indicated by color (20m wrap). The icebergs are clearly discernable in terms of surface size and height.

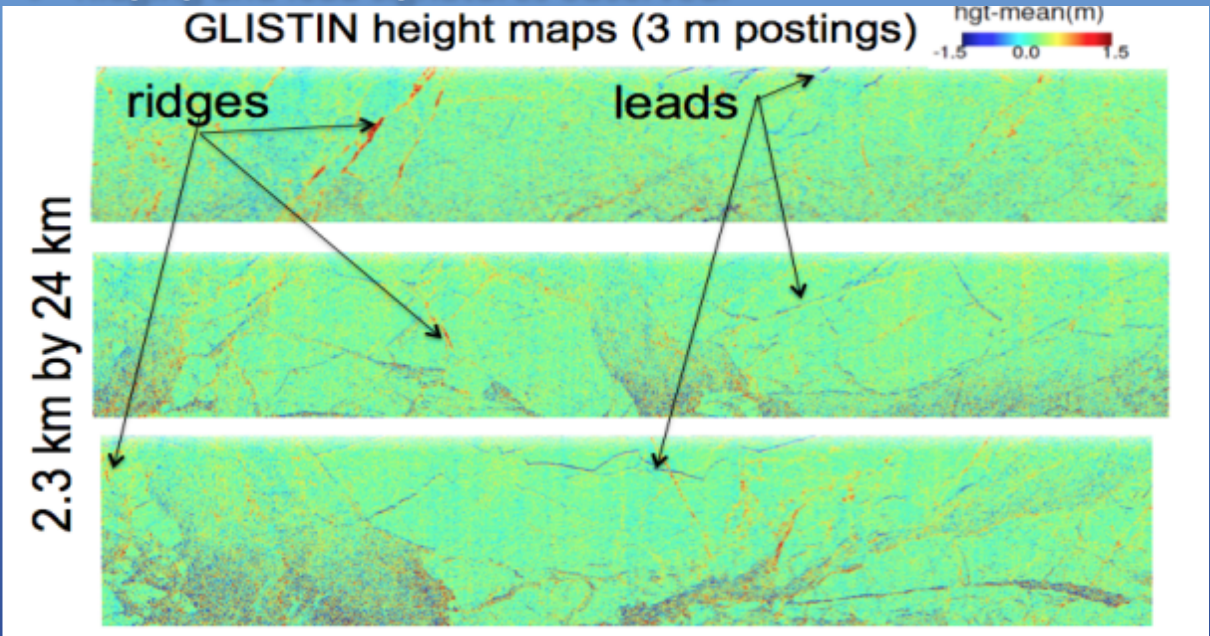
- Below: ocean radial velocity measurements (color indicates velocity). There is ~1m/s difference in surface velocity across the front. Differential velocities between debris and the ocean surface will provide complementary data to the surface height and size distribution for forecasting



Analogous Observations: Sea-ice Freeboard-mapping in the Beaufort Sea

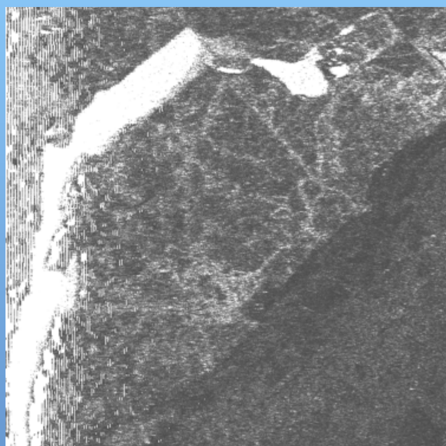
First experimental mapping of sea-ice demonstrating free-board measurement viability using mm-wave ifSAR

- 6 lines collected in total (16800 square-km mapped).
- First line was coordinated with a Cryosat II overpass.
- Height precision ranges from 15cm near-range to 1.5m far range (3m x 3m posting).
- Ridging and lead signatures observed.



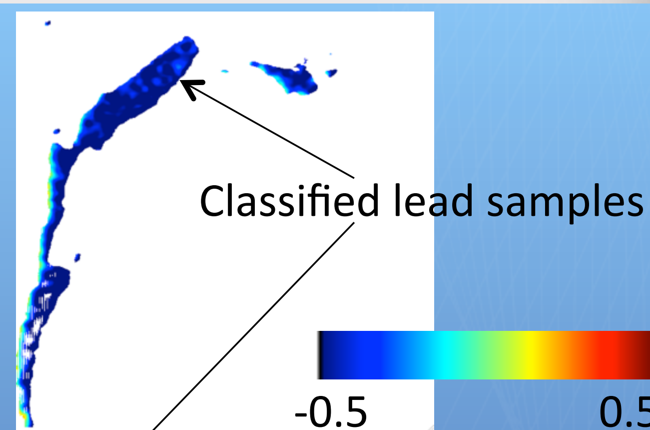
Specular lead return – near range

Specular Pixels Elevations



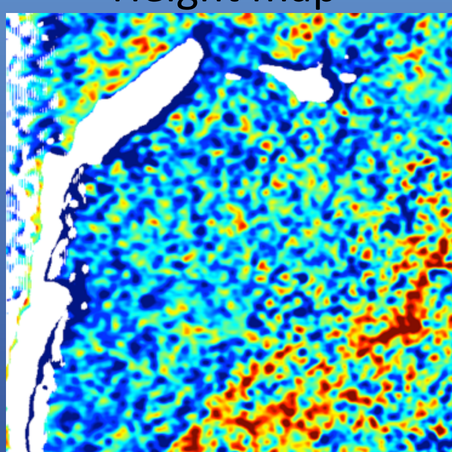
Image

Image size: 600x600 pixels

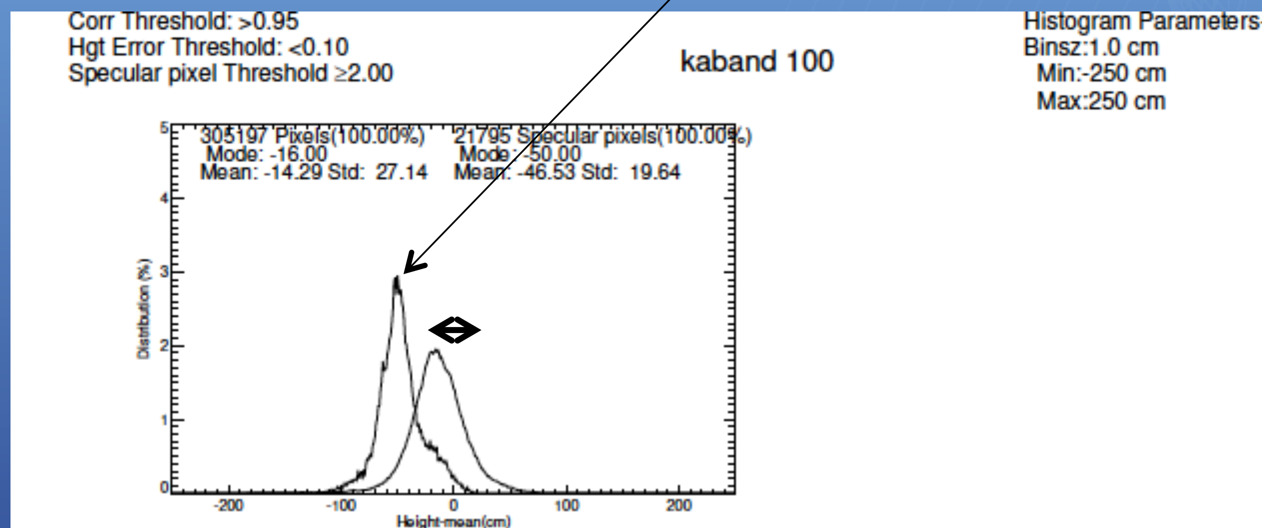


th=2.

Height map



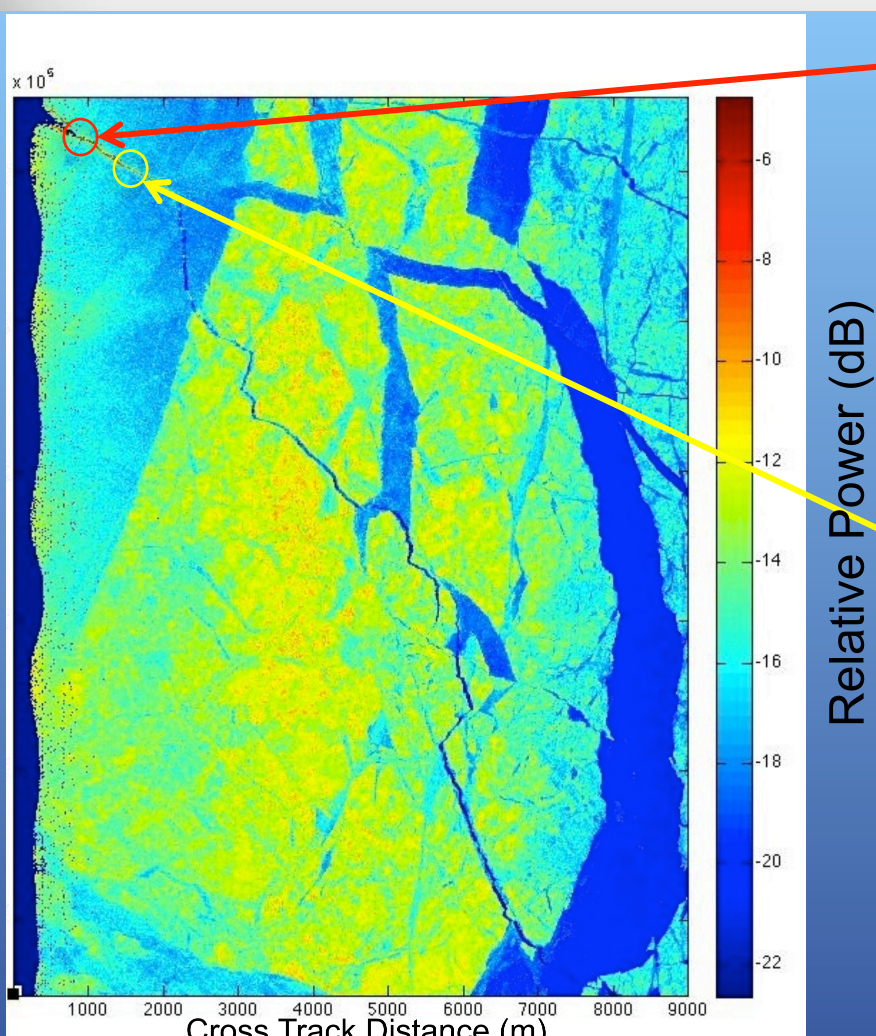
Averaging box size:9x9

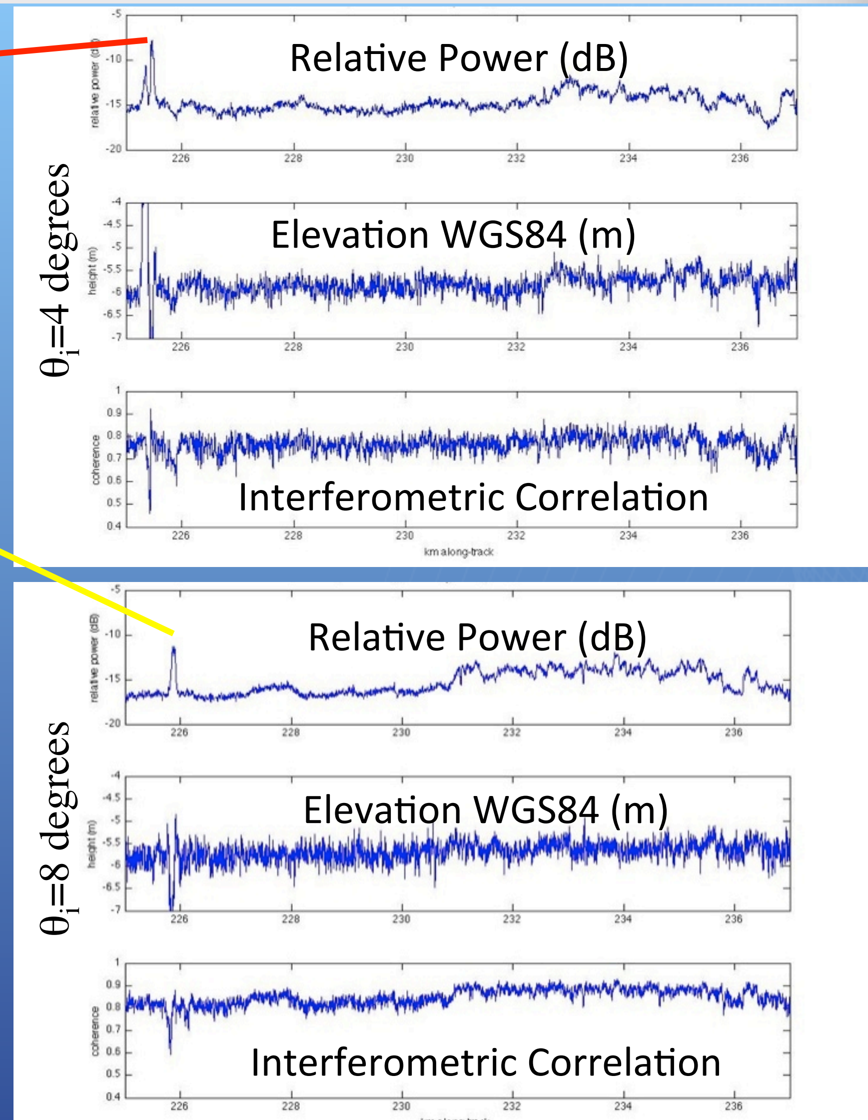


Freeboard ~30 cm

*viewgraph/analysis courtesy of Ron Kwok (JPL)

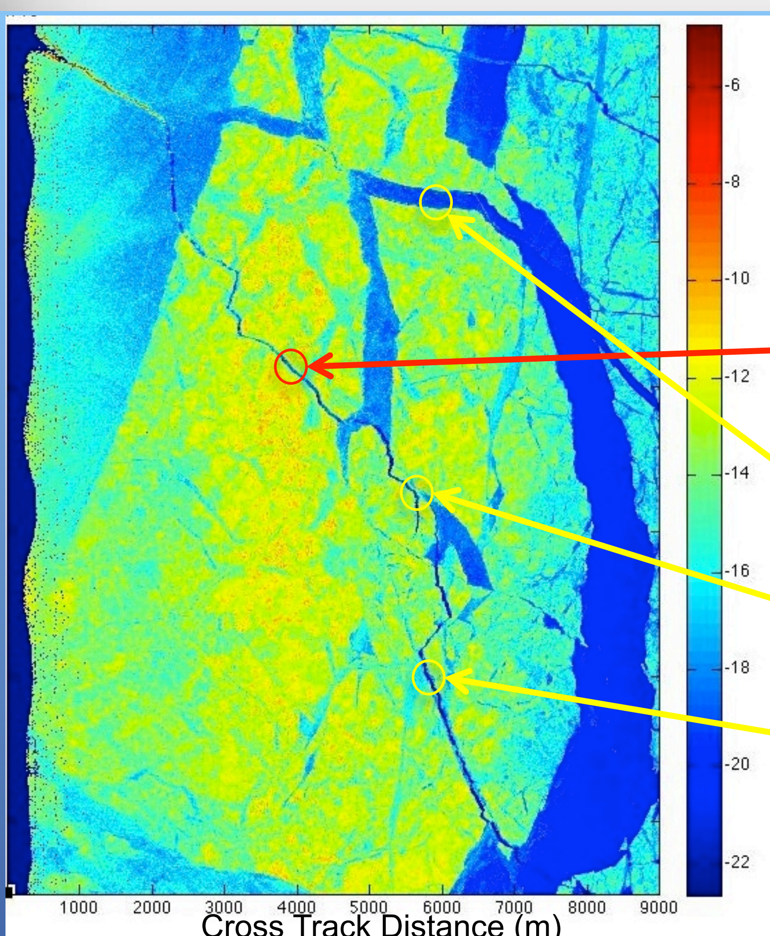
Example: Lead Near-Far range

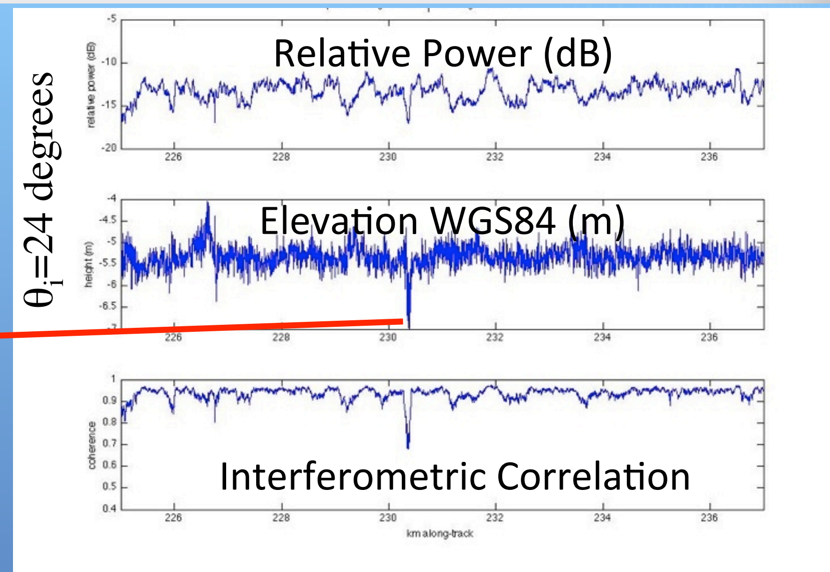


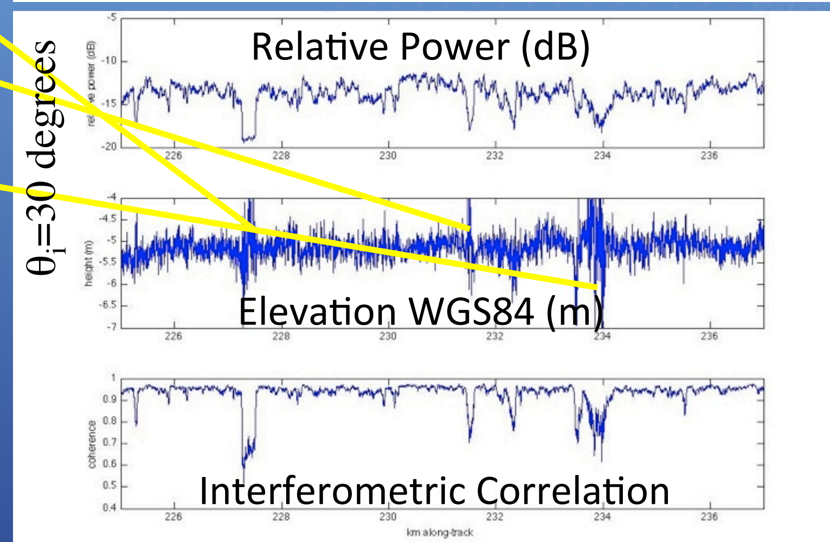


- Specular scattering from leads in near-range allows for freeboard height measurement.

Example: Lead Near-Far range (continued)

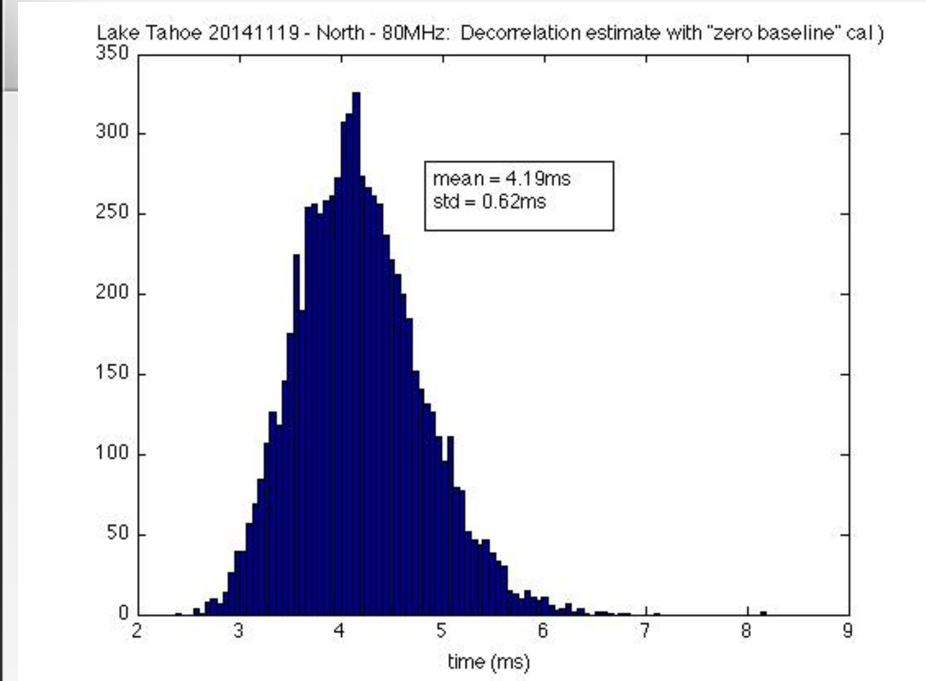






- At moderate incidence angles, lead correlation is sufficient to enable freeboard measurement with averaging and robust classification.
- However, the geoid height is consistent over swath (10km) scales such that nadir free-board measurements can calibrate swath measurements from the the prior pass.

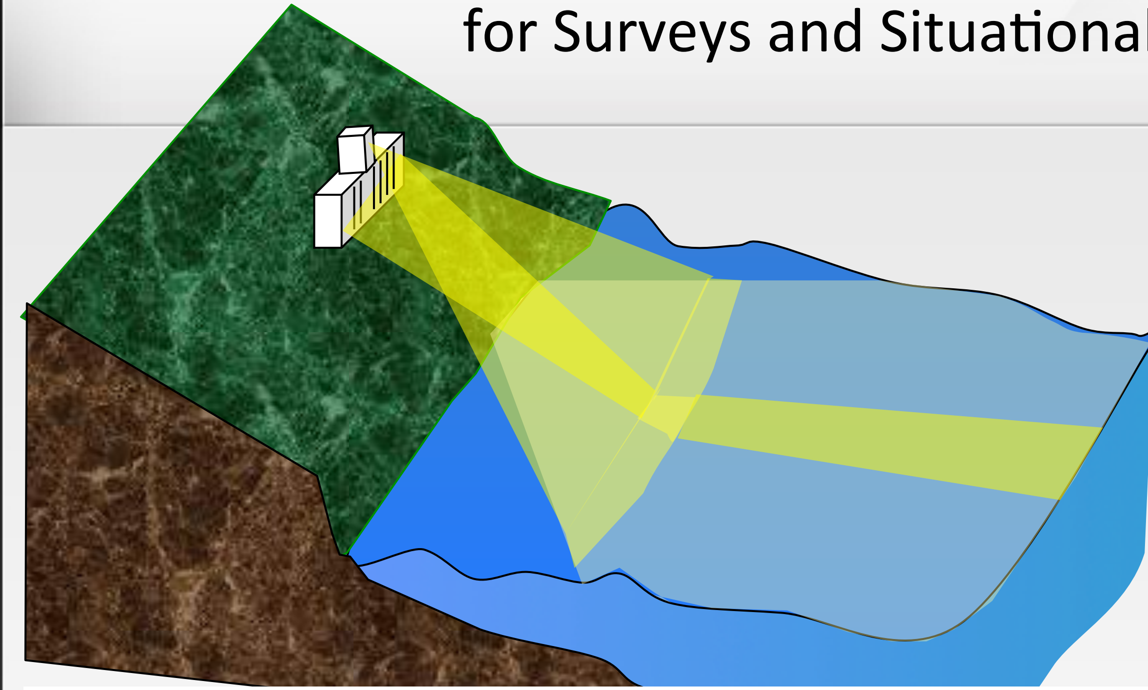
The use of correlation time to classify debris?



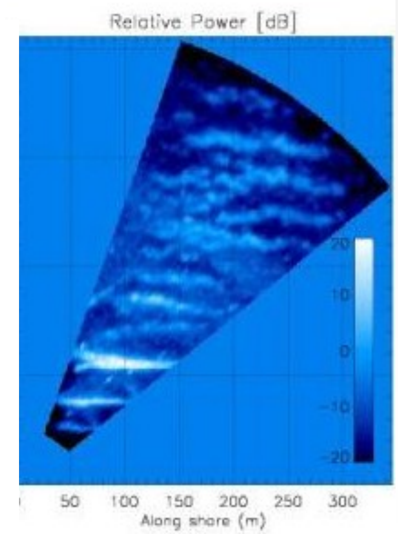
- Experimental observations of ocean/open water decorrelation time at Ka-band have shown that it can be as short as a few ms
  - For the ocean that such short times are expected
- However, when the return is dominated by “specular” scatter (ie debris with a surface signature such that the surface is quelled) the correlation time is significantly longer.
- Not only does along-track information provide surface velocity information for relative dispersion of debris contaminated regions, but also the temporal coherence can provide an effective “classifier”.

Moller, D. and D. Esteban-Fernandez, "Near-Nadir Ka-band Field Observations of Fresh Water Bodies", *Remote Sensing of the Terrestrial Water Cycle*, 1st ed., John Wiley, 2014

Shore Concept for Continuous Area Monitoring or Ship-based for Surveys and Situational Awareness



- Single wide-beam transmitter illuminates area
  - -Azimuth sector ~ 60°
- Complex returns are received by a digital beamforming array
  - -Azimuth pixel ~3° (nominal)
- Time of return discriminates range
  - -Ground Range resolution ~=4m
- Spatial and temporal interferometry enables accurate determination of water level and velocities
- If an object "persists" on the surface (even in troughs) it will be detected through temporal integration.



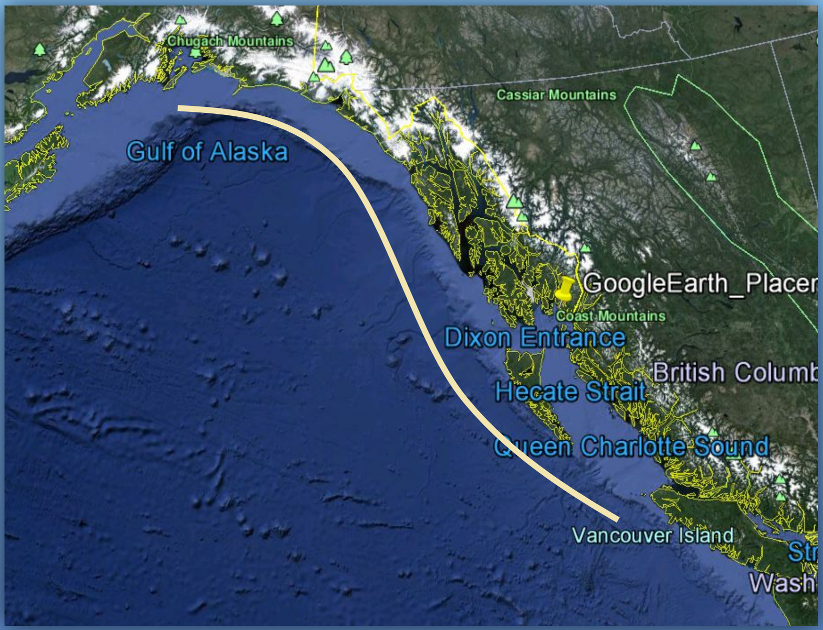
Suborbital/UAS Concept

- Potential for large area/long-term monitoring of oceanic regions for debris detection and transportation/ trajectory monitoring
  - Independent of solar illumination
  - Through fog and cloud
- Primary measurements, geolocated debris field mapping
  - Size and location distribution
  - Smallest objects identified if in "clusters"
- Slow flight speeds can be an advantage to capitalize on temporal integration and "persistance"

New Solara 50 (above) from Titan aerospace (now bought by Google) is to be capable of operating from 65kft for 5 years

- fleet of UAS could persist over the major ocean debris fields
- Compatible with sensor SWAP (at Ka-band including antenna real-estate and baselines)

Example Debris Con-OPS
Continuous Flight Line



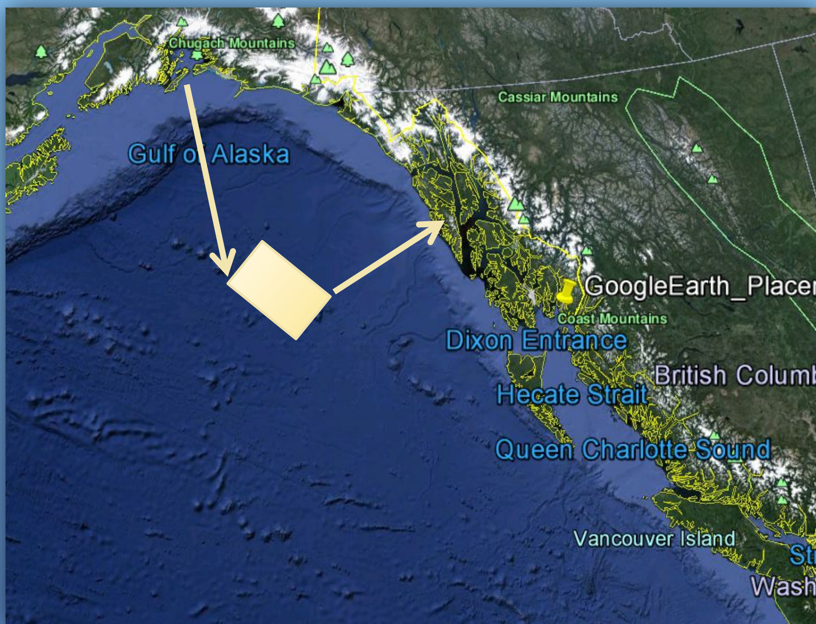
- Daily coverage range from Bellingham, Wa. to Anchorage, AK.
- 2,700 Kilometer mile flight lines
- 15,000 Sq. Kilometers of Ocean coverage
- Survey speed 550 Kph
- Flight level altitude 41,000
- Ability to survey through inclement weather (fog, clouds, light rain, day or night)
- Similar strategy for pollutant monitoring and dispersion and search and rescue

Suitable Aircraft Bases:

- Anchorage
- Juneau
- Ketchikan
- Bellingham, Wa

*slide and scenario courtesy of Joseph "Ben" Hovelman, Mtn High Aviation LLC

Example Con-OPS
Loiter or Block Survey



Operations:
•Depart Anchorage
•Land Juneau
Alternates:
•Yakutat
•Ketchikan
*survey block area not to scale

- 800 km offshore
- 500 kph survey speed
- 100 x 200 km survey block
- 10 km swath
- 20,000 Sq.km coverage
- 20% overlap on survey lines
- Flight level altitude 41,000
- > 8 hours endurance

Satellite Observations

- Greatest spatial coverage usually at the expense of temporal repeat and spatial resolution (maybe)
- Role maybe to provide supportive current/sea-state oceanic observations?
- Land->ocean input (SWOT relevant for river discharge pathways and coastal input?
  - Identifying the “best” orbit can be challenging and constraining
  - Should begin to look at coverage/repeat/resolution scenarios and requirements as part of this workshop
- New launch capabilities coming on line, especially in the commercial sector e.g.
  - Planet labs
  - Rocket labs

Proposed Demonstration

- Could conduct controlled experiment
  - Sample over a variety of wind conditions
    - High resolution (~1m^2) measurements of σ_0 and τ_c
  - Sample over a variety of atmospheric conditions (fog, drizzle, light rain)
  - Deploy/tow various size and types of “debris”
    - Colocated camera (in visible conditions) can verify positive detection

- Crater lake – Oregon
  - Good vantage point
  - Precedent for prior experiments (ref)

Conclusions

- SAR and ifSAR have the potential for detection and mapping of debris, debris fields and pollutants and some properties of the debris to aid in effective forecasting of it's dispersion
- Compatible with:
  - shore and ship-based deployment for near continuous observation (shore) or situational awareness (ship) high-resolution data along route
  - Suborbital piloted and unpiloted deployment for 10's of km swath mapping at sub-10m scale horizontal resolution (depends on specific requirements)
  - Satellite–based observations for larger spatial coverage.
- Targeted demonstration of basic premise should be undertaken