radar & remote sensing

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Why radar for oceanography?

Despite many operational and theoretical problems, radar imaging of the oceans offers distinct advantages:

1) As an active, or combined emission-reflection, remote sensing system, radar can operate night or day (as contrasted with the passive systems studied so far).

2) Cloud cover is transparent at radar $\lambda$ (typically 1 - 10 cm, or $10^4$-$10^5$ $\mu$m; see table above).

3) Depending on $\lambda$: haze, precipitation, and smoke are transparent to radar. (Remember that scattering per spherical raindrop $\propto \frac{R_p^6}{r^2 \lambda^4}$, where $R_p$ is the drop radius; at $\lambda_{\text{radar}} < 1$ cm, heavy rain will reflect strong echoes.)

4) Water is usually opaque at radar $\lambda$, with effective penetration depths of 0.1 mm–10 cm. (Water is most transparent to P-band radar; see Rees, Fig. 3.9). Ice and dry land are not nearly so opaque, which makes radar a useful tool for distinguishing water from ice.

Rees, Fig. 3.9: Schematic absorption lengths of various materials. Absorption lengths are strongly influenced by such factors as temperature and the content of trace impurities, especially at low frequencies.
Radar imaging has yielded such remote-sensing knowledge as:

1) clearly resolved ocean surface waves (\textit{i.e.}, scattering confined to surface \rightarrow sea-surface profile),
2) clear ice-water boundaries in the often-cloudy polar regions,
3) shallow-water imaging of the ocean bottom via surface changes in radar reflectance (see Rees, Fig. 8.9),
4) imaging of internal ocean waves (again, via surface changes in radar reflectance).

Radar may yet be able to distinguish among different types of sea and freshwater ice, an ability currently beyond current visible and IR systems.

For now, these radar advantages are offset by some non-trivial \textbf{disadvantages}:

1) Radar image processing sometimes requires Herculean computer processing, making the resulting data expensive.
2) If a single radar $\lambda$ is used on a given satellite, multispectral analysis is ruled out.
3) Because radar is a \textit{coherent} EMR source (fixed wave phase relationships within the emitted beam), small-scale variations in surface topography (small compared to $\lambda$) will cause interference noise (\textit{speckle}) in the reflected energy. Speckle can be reduced by combining several SAR images of the same scene (\textit{multiple looks}).

However, this disadvantage is offset by a coherent-radiation advantage, since \textit{polarization} of the emitted and reflected beams yields additional information not available in incoherent EMR (e.g., reflected solar and emitted terrestrial EMR).

4) Some theoretical issues in backscatter of radar EMR limit our ability to exploit the data (same also true of visible and IR data).

\textbf{types of radar sensors}

1) \textbf{scatterometers} -- measure a small region’s area-normalized (\textit{i.e.}, dimensionless) backscatter cross-section $\sigma^0$ as a function of incidence angle $\theta_0$ (here, the angle between the nadir and transmission directions). \textbf{N.B.:} Although $\theta_0$, $\theta$, “nadir angle,” and “incidence angle” are used interchangeably, the optical incidence angle clearly depends on the tilt of the surface being illuminated. Strictly speaking, all four terms above are equivalent \textit{only} if the platform looks at a flat surface that parallels a plane tangent to the earth’s surface at nadir.

2) \textbf{imaging radars} -- form radar reflectance images analogous to visible images

Specific types include:

\textbf{a}) side-looking airborne radar (SLAR, a \textit{real-aperture} radar) — high spatial resolution (at low altitude) via time-analysis of a short radar pulse
\textbf{b}) synthetic aperture radar (SAR) — at cost of much computation, avoids some inherent physical limitations on SLAR’s spatial resolution.
some radar theory

The power (in, say, Watts) scattered into an incremental solid angle \( d\Omega_s \) by a surface illuminated with an EMR signal of power \( P_0 \) is given by:

\[
\Delta P_s = \frac{\gamma P_0 \, d\Omega_s}{4\pi}. \quad \text{(Eq. 1)}
\]

\( \gamma \) is a bidirectional scattering coefficient, a dimensionless measure of how reflective the surface is as a function of incidence (\( \theta_0 \)) and reflectance angles. Does Eq. 1 make dimensional sense?

Often \( \gamma \) is rewritten as a backscattering cross-section \( \sigma \), analogous to \( C_{\text{ext}} = 2\pi R_p^2 \), the non-directional extinction cross-section for large spheres. Here, \( \sigma = A\gamma \cos(\theta_0) \), where \( A \) is the area that is being illuminated. As was true for \( C_{\text{ext}} \), \( \sigma \) is an area (however, note that \( \sigma^0 \) is a dimensionless cross-section/area). Unlike our definition of \( C_{\text{ext}} \), \( \sigma \) depends on both incidence and reflection angles.

When the transmitting and receiving antennas are coincident, the power \( P_r \) received from a surface that is at a distance \( R \) is given by:

\[
P_r \propto \frac{P_t A_r \sigma}{R^4}, \quad \text{or,} \quad P_r \propto \frac{P_t \lambda^2 \sigma}{R^4}, \quad \text{(Eq. 2)}
\]

where \( A_r \) is the effective area of the antenna and \( \lambda \) is radar wavelength (see Rees, p. 149). Note that scatterers need not be small compared with \( \lambda \) here, so that the Rayleigh scattering efficiency of \( \lambda^{-4} \) doesn’t always apply (additional Eq. 2 wavelength-dependence is contained in \( \sigma \)).

One problem with our definition of \( \sigma \) (\( \sigma = A\gamma \cos(\theta_0) \)) is that it contains an area, a factor that is inconvenient to continually specify. To avoid this, we use a dimensionless version of \( \sigma \), denoted as \( \sigma^0 \), the backscattering cross-section per unit surface area. (N.B.: \( \sigma^0 \) does not mean \( \sigma \) raised to the zero power!)
\( \sigma^0 \) and polarization

We can linearly polarize radar EMR electronically both on transmit and receive. Like ordinary unpolarized light, radar EMR can also be partially polarized by reflection. (Recall the changing radiances of overhead lights reflected by the tile floor.) It turns out, not surprisingly, that \( \sigma^0 \) also depends on polarization.

In remote sensing, the polarization component parallel to the scattering plane is termed the vertical polarization, and the perpendicular component is called the horizontal polarization. Subscripts \( \text{H} \) and \( \text{V} \) are commonly used to denote the different polarizations. Note that “horizontal” and “vertical” only make sense if the scattering surface is horizontal and the scattering plane is \( \perp \) to it.

Thus terms like \( \sigma^0_{\text{VV}} \) are used to indicate such distinctly non-intuitive notions as a “backscattering cross-section per unit surface area for the vertically polarized reflected component of vertically polarized transmitted radar EMR”!

Remembering that crossed linear polarizers transmit no EMR (at least ideally), do terms such as \( \sigma^0_{\text{HV}} \) make any sense (i.e., can we receive any vertically polarized signal from a transmitted beam that was polarized horizontally)? Yes, \( \sigma^0_{\text{HV}} \) can be nonzero, provided that the reflecting surface changes the original beam’s polarization state, which is possible for reflection by either water or earth.

Because different materials (and their variations; e.g., different kinds of soil) interact differently with polarized radar, we can use these differences to help distinguish among the materials. In other words, polarization differences alone will not solve all radar remote sensing problems.
scatterometry

In addition to polarization and incidence angle, $\sigma^0$ also depends on surface roughness, just as any other EMR source does.

Fig. 3.2. Schematic illustration of different types of surface scattering. The lobes are polar diagrams of the scattered radiation. The length of an imaginary line joining the point $S$ (where the radiation is incident on the surface) to the lobe is proportional to the amount of radiation scattered in the direction of the line. (a) specular; (b) quasi-specular; (c) Lambertian; (d) quasi-Lambertian; (e) complex. Note the increased scattering in the specular direction from most real surfaces.

We may simply want to know how $\sigma^0$ varies with incidence angle $\theta_0$ over some surface area, without analyzing the small-scale variability of $\sigma^0$ within that area. With this kind of analysis, we can distinguish among areas of ocean, vegetation, rock, and ice.

The scatterometer sends out either a continuous or a pulsed radar signal, and the power of the reflected signal (see Eq. 2) partly determines $\sigma^0$ for the imaged area. Either airplanes or satellites can carry scatterometers.

Fig. 8.2. Doppler scatterometer. The radar emits a broad beam of width $\Delta\theta$, but radiation scattered from the point $X$ (at incidence angle $\theta_0$) can be identified by its Doppler shift.

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We can either aim a narrow-beam scatterometer at a target area, or we can use Doppler frequency shifts in the reflected signal to determine the particular \( \theta_0 \) from which the radar is transmitting. Specifically, the frequency shift \( \delta \nu = \frac{2 \nu_0 \nu \sin(\theta_0)}{c} \), where \( c \) is the speed of light, \( \nu \) is the scatterometer’s linear velocity, and \( \nu_0 \) is the transmitted frequency. Note that while \( \nu/c \) is minuscule, \( \nu_0 \) is huge (= \( c/\lambda_0 \)), so that \( \delta \nu \) is readily measurable. Thus the \( \nu \) power spectrum tells us how the reflected power varies with \( \theta_0 \).

In principle, a graph of \( \sigma^0(\theta_0) \) for a perfect mirror should be a delta function. This delta function would consist of a \( \sigma^0 \) spike at \( \theta_0 = 0^\circ \) and \( \sigma^0 = 0 \) at all other \( \theta_0 \). Based on what we know about specular reflection, why is this so? Conversely, a Lambertian surface should show \( \sigma^0 \propto \cos^2(\theta_0) \) \{since \( \gamma \propto \cos(\theta_0) \}\}. Because both surfaces are idealizations, we are better advised to compile \( \sigma^0(\theta_0) \) for real materials and then use these characteristic curves as classifiers of future scatterometry data.

![Graph of \( \sigma^0(\theta_0) \) for various materials.](from Rees 1990)

In oceanography, scatterometry is used to determine wind speed and direction based on the fact that sea-surface roughness increases with wind speed. Because wave crests and troughs will be \( \perp \) to the wind, anisotropy in the \( \sigma^0(\theta_0) \) roughness patterns provides clues to wind direction.

However, recall the ambiguity in trying to determine wind direction from single visible images of cloud streets and gravity waves. Similarly, a single \( \sigma^0(\theta_0) \) pass will
give only the upwind/downwind line, not the absolute wind direction. To reduce this uncertainty, we need additional sampling passes.

**side-looking airborne radar (SLAR)**

SLAR is a *real aperture radar*, as distinct from synthetic aperture radar (SAR). In SLAR, spatial resolution $R_a$ in the along-track (or azimuth) direction (i.e., \( \parallel \) to the flight path) is \( \propto \frac{1}{L} \), where \( L \) is the transmitting antenna’s actual length. Specifically,

$$R_a = \frac{H \lambda}{L \cos(\theta)} \quad \text{(Eq. 3)},$$

where the remaining parameters are the radar wavelength \( \lambda \), flight altitude \( H \), and the nadir angle \( \theta \). Clearly, resolution improves (i.e., \( R_a \downarrow \)) with: a) lower altitude, b) longer antennas (\( L \uparrow \)), c) steeper nadir angles (\( \theta \downarrow \) and \( \cos(\theta) \uparrow \)).

**from Rees 1990**

In the *cross-track* direction (or *range* direction; \( \perp \) to the flight path), it is the pulse length \( \tau \) of the radar that determines resolution \( R_r \). Setting \( \tau = \frac{1}{\Delta v} \) and noting that \( \Delta v \) is the signal bandwidth (\( \Delta v = \Delta\text{-frequency} \)), we have:

$$R_r = \frac{c \tau}{2 \sin(\theta)} \quad \text{(Eq. 4)},$$

where, as earlier, \( c \) is the speed of light.
A. CROSS-TRACK SCANNER.

B. CIRCULAR SCANNER.

D. SIDE SCANNING SYSTEM.

C. ALONG-TRACK SCANNER.
Calculate the values of $L$ and $\tau$ required to yield $R_a = R_r = 20$ meters for a 10-cm wavelength SLAR in an aircraft at 1000 meters above the surface which looks at a target 360 meters from its nadir position. Is $R_a$ or $R_r$ degraded less in this example if the airplane $H$ increases to 2 km? Given your answers, does either resolution promise to make a real-aperture radar (such as SLAR) practical on an oceanographic satellite?

Often the slant range $S$ to objects increases uniformly in SLAR images, as Fig. 8.7 from Rees shows.

Since $\cos(\theta) = \frac{H}{S}$, then $S = \frac{H}{\cos(\theta)}$. Thus an image scaled uniformly in $S$ is, at constant altitude, scaled uniformly in $\frac{1}{\cos(\theta)}$. Because we usually want to know how the horizontal ground range increases in an image, uniform-$S$ images are not very intuitively obvious for human analysts.

More serious than this essentially cosmetic mapping problem, however, are two radiometric problems caused by a SLAR’s vantage point: layover and shadowing.

Layover is related to the slant-distance differences between objects’ tops and bottoms. If the object leans toward the radar, these distances will be reduced, but if the object leans away, they will be increased. Thus a horizontally symmetric feature such as a hill will have a bright near side and a darker far side, making its interpretation
difficult if we did not know that the hill was there to start with. (Remember that radar irradiance illuminating the terrain will *decrease* with distance from the transmitter.)

**Shadowing** is an extreme form of layover in which the far side of an object (with a larger slant distance $S$ than the near side) is darker than the near side. In the case of an object completely in radar shadow, we cannot know that it is there. Altitudes may even become reversed at large nadir angles $\theta$.

For example, a hill’s summit can appear brighter (and therefore presumably is closer) than its nearby foot if the slant range to the summit is $< \text{range to the foot}$ (Rees, Fig. 8.7a; Lillesand, Kiefer, & Chipman, Fig. 8.2). The far side of the hill would be invisible to the SLAR.

Finally, random *speckle* plagues all coherent-EMR imaging systems such as SLAR (provided that $\lambda \leq \text{“small-scale” features’ } \Delta S$). Because slant-distances vary rapidly within a small angular field of view for natural terrain, so will the phase relationships of the radar signals reflected by that terrain. This random variation in signal intensity, above and beyond random receiver noise, can be reduced by averaging over several pulses from the moving radar platform.

**synthetic aperture radar (SAR)**

In SAR, the altitude-dependence of SLAR’s along-track range $R_a$ (see Eq. 3) is avoided by analyzing the reflected signals differently. Equation 3 still governs the resolution of the platform’s *physical* antenna. However, sophisticated time analysis of the radar returns makes it possible to *synthesize* a much larger antenna.

We know the signals’ amplitudes and phases as the aircraft (or satellite) moves at forward velocity $v$ over time period $T$. In principle, if we collect data over a large enough $T$, we can reformulate the real signals from the real antenna (of length $L$) as if they were instantaneously collected by a much larger imaginary antenna of length $vT$. Note that $vT$ is the distance that the radar platform has traveled in time $T$; we call this distance the effective aperture (or length) of the synthetic antenna.

SAR’s signal-processing technique is akin to the analysis of Doppler frequency shifts that is used in some scatterometers. At the price of considerable computer time, SAR’s along-track resolution will always be better than a SLAR at the same altitude.

The theoretical issues involved in analyzing SAR data are as formidable as the computations that they drive (see Rees, Sections 8.5.1-8.5.4; Lillesand, Kiefer, & Chipman, Sect. 8.4). Although black-and-white images of SAR data are helpful in guiding human analysts, the actual quantitative analysis relies almost exclusively on computers.

The reward for all of this work is high-resolution images of the earth and oceans from satellites, images that can be gathered independent of weather or time of day. For
example, in Rees’ Fig. 8.9 note that roads ~15-30 meters wide are clearly visible from an altitude of 800 km!

**birefringence and remote sensing**

Our observations of cellophane tape placed between polarizers prompt three questions:

1) what’s birefringence?

2) how does birefringence → colored patterns in polarized light?

3) how are birefringence & dichroism used in radar remote sensing?

**What’s birefringence?**

A birefringent material has not one, but two, refractive indices \( n \), where \( n = \frac{c}{V} \) and \( V \) is the propagation speed of EMR in the medium.

How can a single material have two refractive indices? Easily enough, if we change the illumination’s polarization. (Here, we’ll consider only linear polarization, but other polarization types can also yield different \( n \) in the same medium.)

At a given \( \lambda \), a birefringent medium refracts \( \perp \) and \( \parallel \)-polarized EMR by different amounts. To see the effects of birefringence we rely on dichroism, which is absorption that varies with the incident EMR’s polarization state (e.g., \( \perp \) - or \( \parallel \)-components of unpolarized light). The Polaroid sunglasses and other linear polarizers that we’ve used are (linearly) dichroic filters.

**Birefringence, dichroism, and colored patterns**

The mosaic of colors in the cellophane tape was an example of birefringence in one medium (the tape) made visible by dichroism in another (the polarizers).

The tape does *not* polarize the light incident on it. (How could we demonstrate that?) Instead, it changes the polarization state of incident polarized light.

For example, if the light passing through the first filter were linearly polarized with \( E \perp \) to the top of the screen, birefringence in the tape might alter that polarization so that \( E \) forms an angle of 45° with the top of the screen.

If the second polarizer has its transmission axis \( \parallel \) to the top of the screen, you would expect very little light to be transmitted through the sandwich of materials (*i.e.*, crossed linear polarizers → near-zero transmission). Instead, we see a vividly colored mosaic of cellophane strips.
In fact, these visible effects of the tape’s birefringence depend on:

1) the tape’s angular orientation w.r.t. the incident polarized light’s $E$-vector,
2) the tape’s physical (and thus optical) thickness,
3) the $\lambda$ of the light illuminating the tape.

The tape changes the wave phase difference between the $\perp$- and $\parallel$-components of the transmitted polarized light. Because the phase angle $\delta$ of $E$ in the tape depends on both $\lambda$ and on the tape’s two refractive indices $n_{\perp}$ and $n_{\parallel}$, we see different colors at different tape orientations. Specifically, for a piece of tape of thickness $h$,

$$\delta_{\perp} = \frac{2 \pi n_{\perp}}{\lambda} h \quad \text{and} \quad \delta_{\parallel} = \frac{2 \pi n_{\parallel}}{\lambda} h.$$

So if initially white light has its red and blue $E$-components selectively removed by the second polarizer, but green light is not removed, we’ll see green in the tape.

Why does the tape have different $n_{\perp}$ and $n_{\parallel}$? Because the tape is stretched during manufacturing, its molecules become partially oriented with respect to one another, thus yielding different responses to the $\perp$- and $\parallel$-polarized EMR.

Stretching any transparent plastic can produce this kind of **induced birefringence**, as the colors seen in airplane windows and other transparent plastics indicate. In satellite remote sensing, however, we’re chiefly interested in **natural birefringence**. Ice is naturally birefringent as a result of its ordered, crystalline structure. For the same reason, birefringence occurs in many minerals, including calcite.

**How are birefringence & dichroism used in radar remote sensing?**

In our demonstrations, we saw birefringence’s effects on transmitted visible EMR. In radar imaging, we see the combined effects of transmission and reflection by surface materials. Thus if a sample of a naturally birefringent material were either completely opaque ($t = 0$) or completely transparent ($r = 0$) to radar-$\lambda$, its visible birefringent effects on polarized EMR would be nil.

Barring such pathological cases, how do we exploit the birefringence of naturally occurring materials in remote sensing? By **polarizing the transmitted and the received energy** at the satellite’s (or airplane’s) radar antenna.

As shown in our demonstration, at a given $\lambda$ the radiance of a birefringent material will depend on the orientation of the transmit- and receive-polarizations. We can examine the radiance ratios of an image feature at different transmit- and receive-polarization combinations ($i.e.$, HH, HV, VV, or VH).

Then we compare those ratios with the known polarization reflectance ratios of materials (at the same radar-$\lambda$) that are likely to be in the scene. If we find a match, we have a **possible** identification of the image feature.
Oceanographic applications of radar remote sensing

surface roughness, interference, and ocean wind-waves

For a calm sea, a nadir-viewing ($\theta_0 = 0^\circ$) radar satellite will get a strong, uniform specular return in which $\sigma^0$ varies only slightly. Off-nadir pixels include very little specularly reflected energy (none, in principle).

However, wind stress $\rightarrow$ ocean-surface deformation and waves, so then specular reflection can occur at $\theta_0 > 0^\circ$. From a remote-sensing standpoint, ocean waves produce periodic fields of specular reflections that alternately tilt toward and away from the satellite. But even large seas have wave faces tilted only $\sim 20^\circ$-25$^\circ$ from the horizontal, so specular reflections are important at most for $\theta_0 \sim 20^\circ$.

**strong specular reflections toward** satellite from look angles A & B, but not from C

Ocean swells (with, say, $H = 0.01 \text{ m}$, $L = 300 \text{ m}$) will cause these comparatively large-scale specular reflection patterns in radar images. Their visible-λ counterparts are the glare-and-shadow patterns seen in sunglint.

For $\theta_0 > 20^\circ$, smaller-scale surface roughness features such as small gravity waves (say, $2 \text{ cm} < L < 1 \text{ m}$) influence specular reflectance patterns. For radar wavelength $\lambda_R$ and ocean surface irregularities with height $h_r$ we define:

smooth surfaces as $h_r < 0.04 \lambda_R \cos(\theta_0)$; rough surfaces as $h_r > \lambda_R \left(\frac{\cos(\theta_0)}{4}\right)$.
For ocean surfaces qualifying as rough, some gravity-wave facets are always at normal optical incidence \((i.e., \theta = 0^\circ, \text{ regardless of the nadir angle})\) and so send specular reflections to the satellite sensor. For centimeter-\(\lambda\) radar, like-oriented gravity-wave facets with wavelength \(\lambda_s\) may be separated by integer multiples of \(\lambda_R\).

Thus different gravity waves reflect constructively-interfering radiances to the satellite, and destructive interference occurs for other wave portions. This resonant Bragg scattering is the oceanographic equivalent of alternating constructive and destructive interference seen in a diffraction grating. However, it requires a particular range of gravity-wave \(\lambda_s\), namely:

\[
\lambda_s = \frac{\lambda_R \sin(\phi)}{2 \sin(\theta_0)}
\]

where \(\phi\) is the angle between the radar azimuth and the wave crests.

Individual Bragg scattering peaks obviously are of sub-pixel size, even for radar imaging. However, they do increase \(\sigma^0\) (backscatter cross-section) where resonant-\(\lambda\)
gravity waves exist and where longer-λ waves (or a calm sea) would send the satellite no energy.

For Seasat-1 (operational only during 1978), an L-band SAR with λ_R ~ 23 cm and a θ_0 of 20°, calculate what:
1) size features h_r → a “rough” surface?,
2) gravity-wave λ_s reflected the strongest signals to Seasat-1 (assume φ = 90°)? Qualitatively, why are these results surprising?

These small gravity waves (even capillary waves can affect observed radar radiances) are negligibly important in the total ocean-wave energy spectrum (see Pond & Pickard, Fig. 12.12; note that here the period T << 1 sec).

![Graph](image)

from Pond & Pickard, Introductory Dynamical Oceanography

However, even for wind speeds > a few cm/sec, there are small net energy exports from the capillary- and gravity-wave regimes to longer-period and longer-wavelength waves. So radar remote sensing can provide new information about largely unmeasured wind-wave dynamics.

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As noted above, since surface winds largely determine the sea-surface roughness field, radar backscatter $\sigma^0(\theta_0)$ can be used to derive the surface wind field (e.g., ERS-1 wind scatterometer & similar instruments). Because $\sigma^0(\theta_0)$ depends on both wind speed and direction with respect to $\theta_0$, several measurements of $\sigma^0$ over the same surface area help remove wind-direction ambiguities (see Rees, pp. 152-154). One empirical equation for the relationship between $\sigma^0$ and wind speed and direction is:

$$\sigma^0 = aU^\gamma \{1 + b\cos(\psi) + c\cos(\psi)\},$$  \hspace{1cm} \text{(Eq. 5)}

where $U$ = wind speed, $\psi = \angle$ between wind vector and satellite look direction, and $a$, $b$, & $c$ are all $f(\theta_0, \nu)$. If $\sigma^0(\theta_0)$, $\gamma$, $\theta_0$, and $\nu$ are all known, how many unknowns remain in Eq. 5? At a minimum, how many $\sigma^0$ measurements do we need to solve for $U$ and $\psi$ (jointly, the wind vector)? In what way would having more $\sigma^0(\theta_0)$ measurements improve estimates of $U$ and $\psi$?

**ocean waves, remote sensing, and surface films and slicks**

Not only wind, but also the properties of the ocean surface itself, determine $\sigma^0(\theta_0)$. Oil slicks, biogenic surface films, phytoplankton blooms, and certainly whitecaps all affect backscattered radar reflectivity. Although air is transparent at radar $\lambda$, multiple scattering by air bubbles in water can increase backscattering, just as multiple scattering by water droplets (or ice crystals) in air does.

Surface films are organized by near-surface currents, and so surface convergence concentrates the films while divergence disperses them (see Robinson, Fig. 10.4 below). Small-scale gravity waves and capillary waves are damped out by the decreases in surface tension associated with surface films. Because lower surface tension makes the ocean surface more elastic (i.e., more “stretchable”), restoring forces are greater for a given wind speed than they would be without the film. These greater restoring forces in turn damp out the small-scale gravity and capillary waves.
Clearly, a smoother sea surface is more nearly a specular reflector, and except for cases where the optical incidence angle (as opposed to the nadir angle) $\theta = 0^\circ$, slicks and films $\rightarrow$ dark areas on radar images.

from I. S. Robinson, Fig. 10.4: Surface convergence thickens surface films and forms a line of surface debris.

However, detectable slicks and films may:
1) form without surface current convergence (e.g., in response to internal waves, including their breaking form, oceanic Kelvin-Helmholtz billows),
2) may fail to form in a sufficiently rough sea, even if convergence is strong.

Thus dark ocean areas in radar images are not infallible indicators of surface convergence.

Furthermore, surface convergence can either smooth or steepen existing gravity waves, thus yielding either decreased or increased surface roughness (and thus $\sigma^0$ changes). When the convergent current flows opposite to the wave direction, the net wave speed $\uparrow$, its energy is concentrated and wave height $\uparrow$, resulting in wave breaking and $\sigma^0 \uparrow$. Not surprisingly, all of these energy changes are reversed and $\sigma^0 \downarrow$ when the convergent current flows with the waves.

from I. S. Robinson, Fig. 10.6: Surface convergence produces wave steepening and possibly breaking, enhancing surface roughness.

Ships under way generate both short-lived turbulent and longer-duration Kelvin wakes (nominal 19.5° half-angle). Any trailing oil slicks will prolong the ship track beyond its natural lifetime and make the turbulent-wake area appear dark in radar images. However, wake turbulence’s immediate effect is to increase surface scattering and thus $\sigma^0$. So in a ship wake we could expect to see:
1) a wide Kelvin wake that may quickly merge with a swell pattern,
2) if oil is discharged in sufficient quantities, a narrow dark wake (~ same width as bright turbulent wake) persisting at greater distances as the sea surface settles and specular reflection away from the satellite dominates.

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Summary

- At swell wavelengths, tilted wave surfaces → alternating specular reflections toward & away from active radar-λ satellites.
- Thus swell and internal waves appear as periodic dark & light bands in SAR images.
- Constructively interfering specular reflections from sub-pixel sized capillary & gravity waves (resonant Bragg scattering) can ↑ surface roughness, radar backscattering cross-section $\sigma^0(\theta_0)$ and thus ↑ image brightness.
- Measurements of $\sigma^0$ from several look angles can → estimates of surface wind vectors.
- Films and oil slicks damp out gravity & capillary waves → dark areas of specular reflection away from the satellite.
- Surface convergence concentrates films & slicks, which causes $\sigma^0(\theta_0)$ ↓.
- Conversely, surface convergence can steepen & break gravity waves, which causes $\sigma^0(\theta_0)$ ↑.
- In ship wakes, slicks (specular reflection) and wake turbulence (multiple scattering) → opposite changes in $\sigma^0(\theta_0)$. 

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