An introduction to Synthetic Aperture Radar observations

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From imaging radars to Synthetic Aperture Radars

Synthetic Aperture Radars (SARs) are advanced forms of side-looking imaging radars.

A Radar is a **RA**dio **D**etection **A**nd **R**anging sensor. Radars are used in many contexts, including meteorological detection of precipitation, measuring ocean surface waves, air traffic control, police detection of speeding traffic, and by the military.

There are active and passive radar sensors:

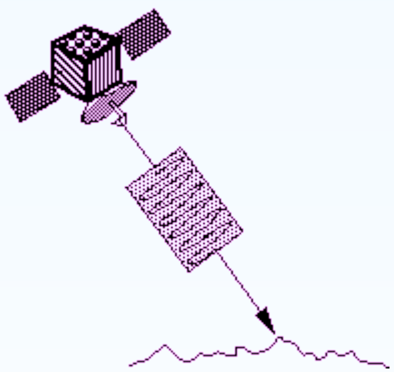
Passive radars: radiometers

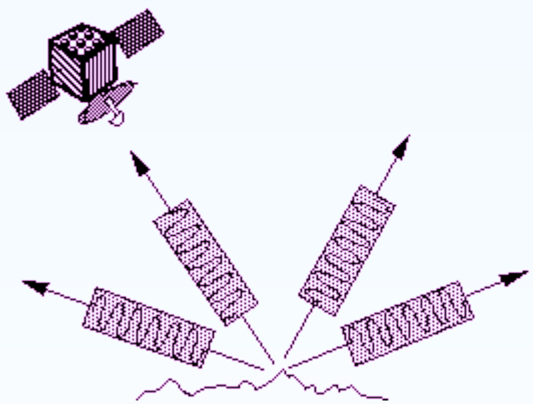
Active radars: Radar imaging systems (SARs), Scatterometers, Altimeters

Radar imaging systems: *how do they work?*

A radar is essentially a ranging or distance measuring device.

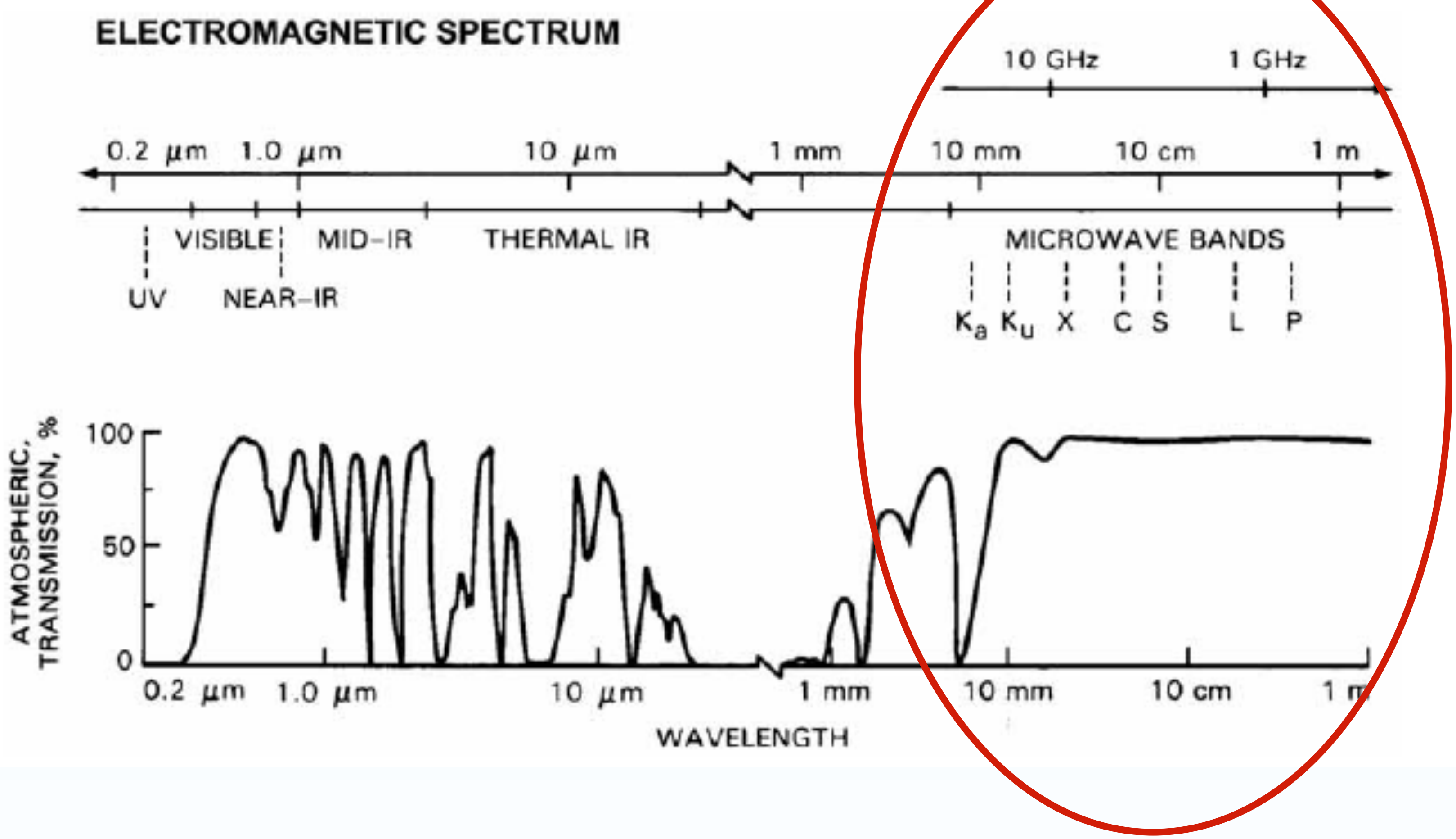
It consists fundamentally of a transmitter, a receiver, an antenna, and an electronics system to process and record the data. The same antenna is often used for transmission and reception.





By measuring the time delay between the transmission of a pulse and the reception of the backscattered "echo" from different targets, their distance from the radar and thus their location can be determined.

Radar imaging systems: frequencies and bands

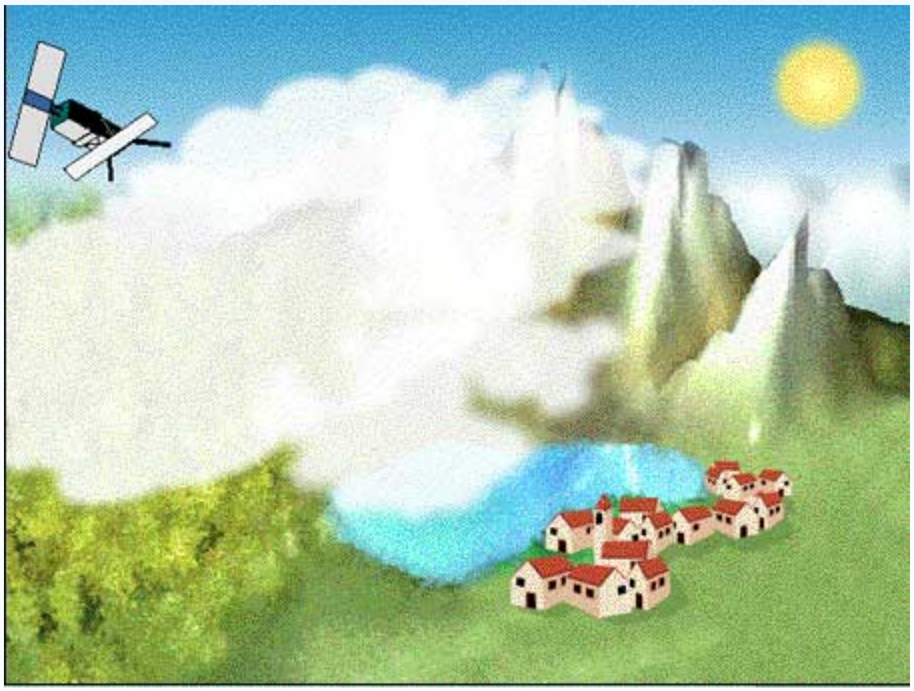


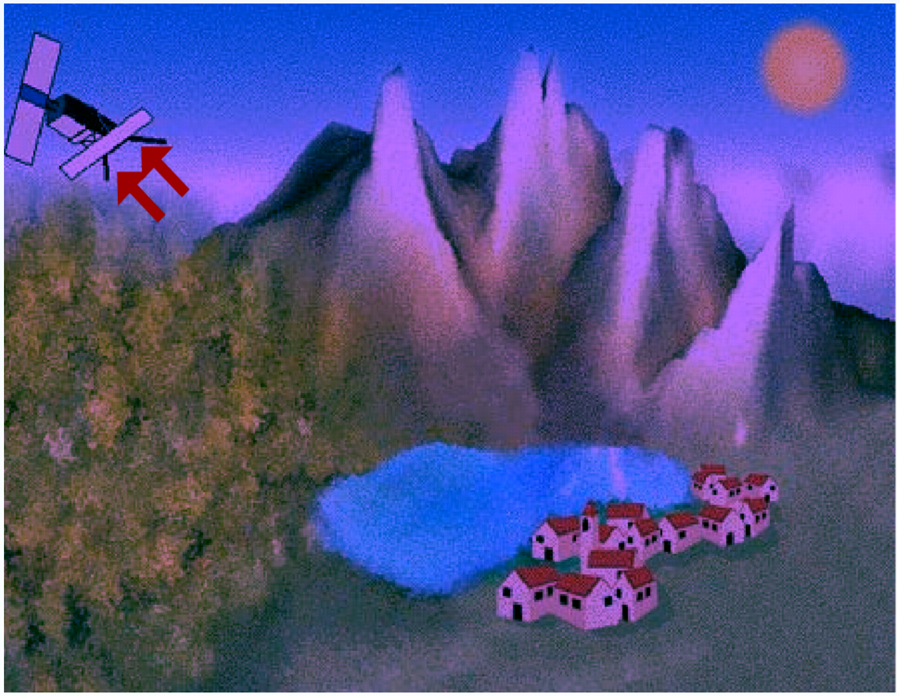
The microwaves emitted and received by SAR are at much longer wavelengths (5.6cm for ERS SAR) than optical or infrared waves.

Radar imaging systems: frequencies and bands

Measurements through clouds
Images can be acquired independently on the current weather conditions

Measurements day and night
Images independent of solar illumination, which is particularly important in high latitudes (polar night)





SARs are well suited to surveillance and disaster managements

- **Maritime surveillance:** ice detection, oil and ship detection

But SARs are also used for many other reasons

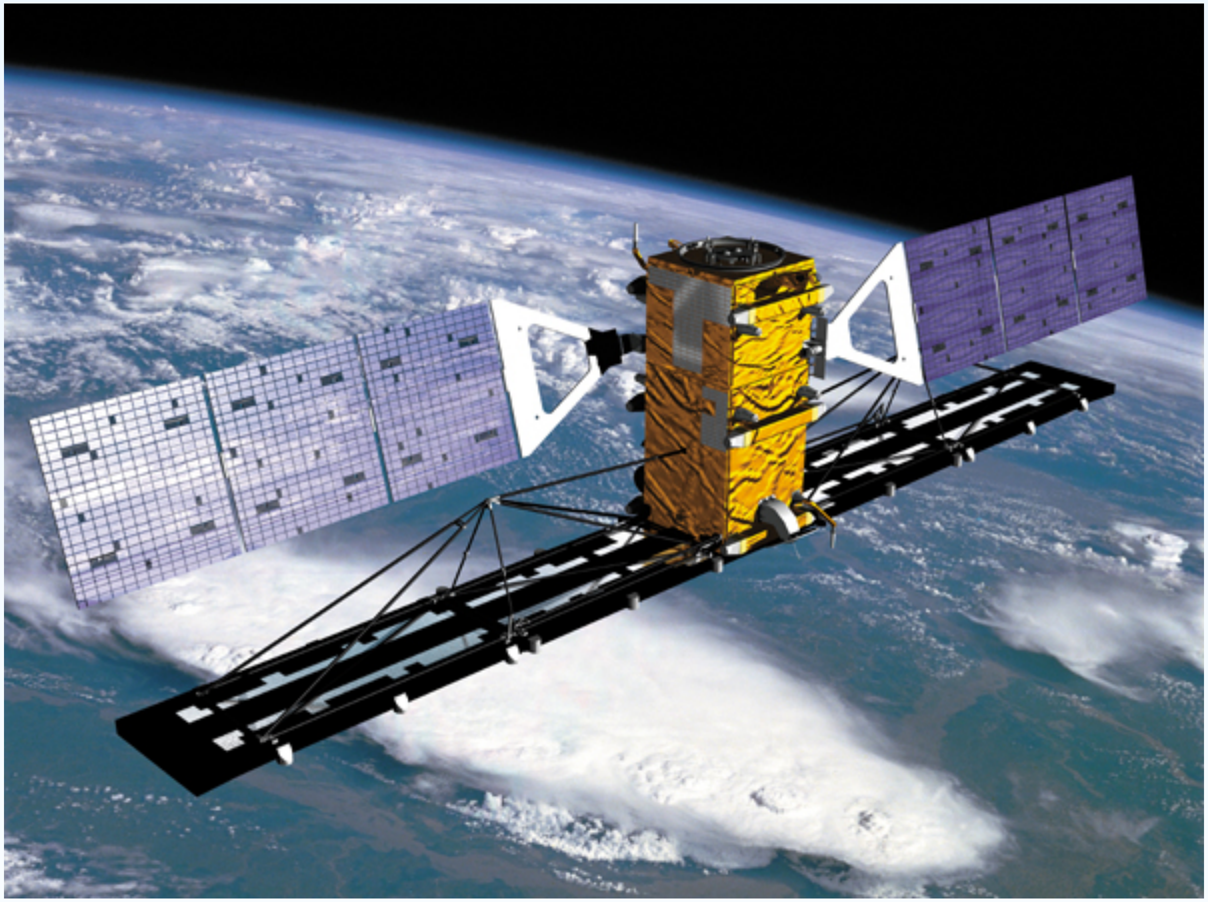
- **Maritime safety:** ocean wind speed, atmospheric fronts, waves, currents, eddies, internal waves
- **Geology:** accurate measurements of distance (interferometry), surface change, coastal erosion, measuring glacier motions, detecting effect of earthquakes
- **Hydrology:** estimating soil moisture, surface water content

Spaceborne SARs

Satellite	Years	Agency	Frequency - Polarisation	Resolution - Swath	Special
ERS-1	1991-2000	ESA	C - VV	25 m 100 km	Interferometry (with ERS-2)
JERS	1992-1998	NASDA	L-HH	25 m 100 km	Region. mosaic available
ERS-2	1995	ESA	C - VV	25 m 100 km	Interferometry (with ERS-1)
RADARSAT-1	1995	CSA	C - HH	10 -100 m 45 - 500 km	Multi-incidence
ENVISAT - ASAR	2002	ESA	C - HH/VV/HV	25 - 1000 m 50 - 500 km	Multi-incidence
ALOS - PALSAR	2006	JAXA	L - Polarimetric	10 - 100 m 100 - 350 km	Multi-incidence
TerraSAR-X Cosmo-Skymed	2007	DLR Italy	X-Polarimetric	1 m	Interferometry (1 day)
RADARSAT 2	2008 ?	CSA	C - Polarimetric	< 10 m	Multi-incidence

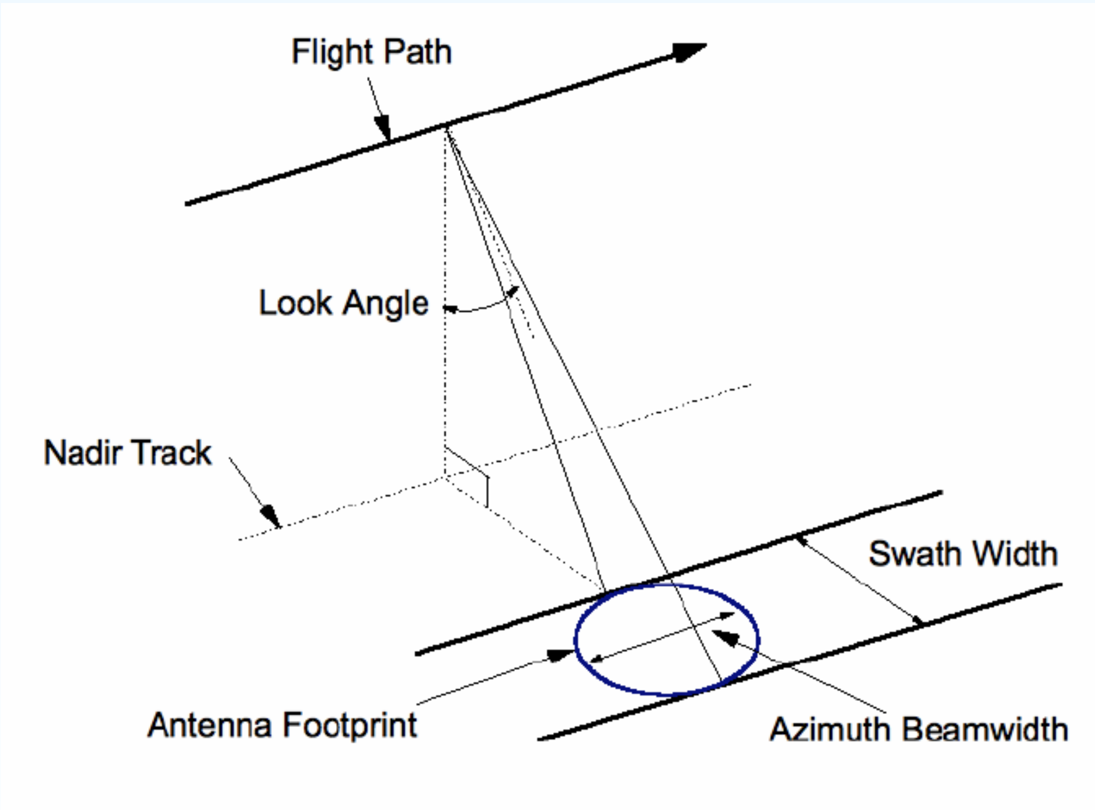
ERS -2 and Envisat in tandem flight

Radarsat - 2



Sentinel – 1
Planned for launch in 2013

Radar imaging systems: *imaging geometry*



Most imaging radars used for remote sensing are side-looking airborne radars (SLARs) to avoid ambiguities.

The antenna points to the side with a beam that is wide vertically and narrow horizontally.

Azimuth = flight direction

Range = perpendicular to the flight Direction

Swath = 100 to 500km

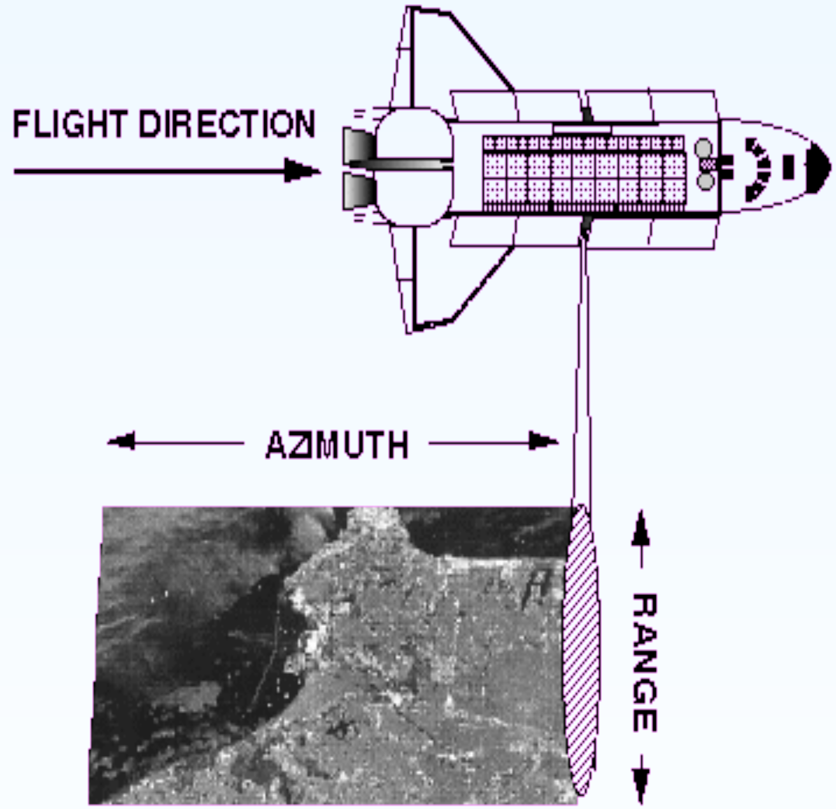
Radar imaging systems: ***building a 2D image***

A pulse of energy is transmitted from the radar antenna.

The amplitude and phase of the backscattered signal is recorded as a function of time.

This is repeated over again while platform is moving.

As the sensor platform moves forward, recording and processing of the backscattered signals builds up a two-dimensional image of the surface.



Radar imaging systems: *how do they work?*

The SAR measures the power of the reflected signal, which determines the brightness of each picture element (pixel) in the image. Different surface features exhibit different scattering characteristics:

Urban areas: very strong backscatter
Forest: medium backscatter
Calm water: smooth surface, low backscatter
Rough sea: increased backscatter due to wind and current effects

Radar imaging systems: how do they work?

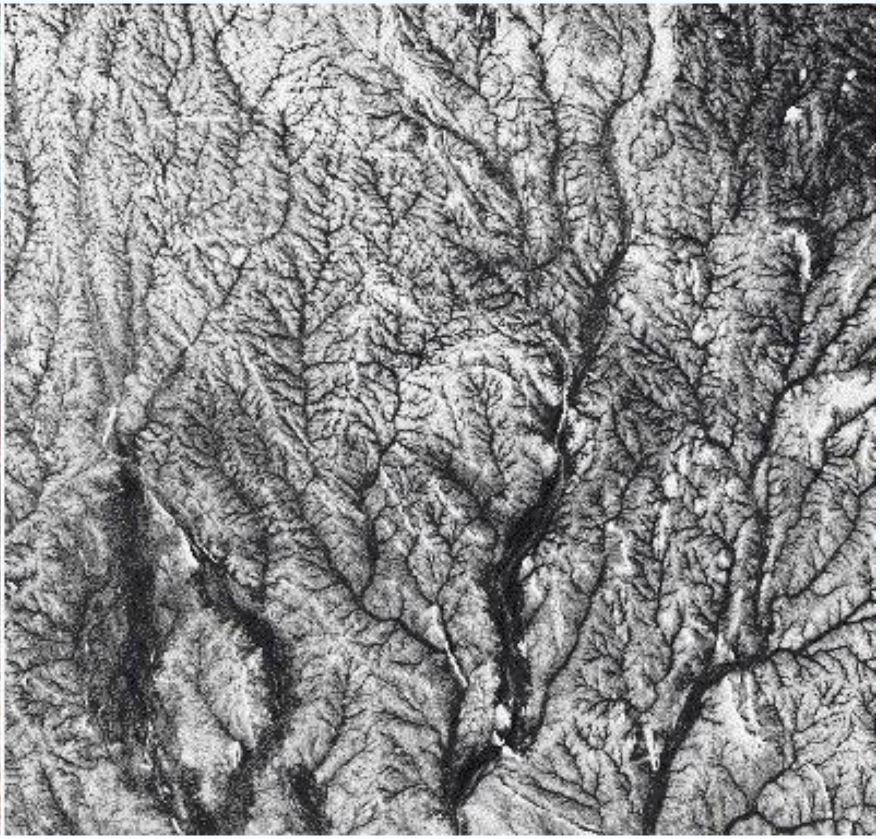
The radar backscattering is a function of: frequency f, polarisation p and incidence angle of the electromagnetic waves emitted

If we consider the example of a forest, the radiation will only penetrate the first leaves on top of the trees if using the X-band (= 3 cm).

In the case of L-band (= 23 cm), the radiation penetrates leaves and small branches; the information content of the image is then related to branches and eventually tree trunks.

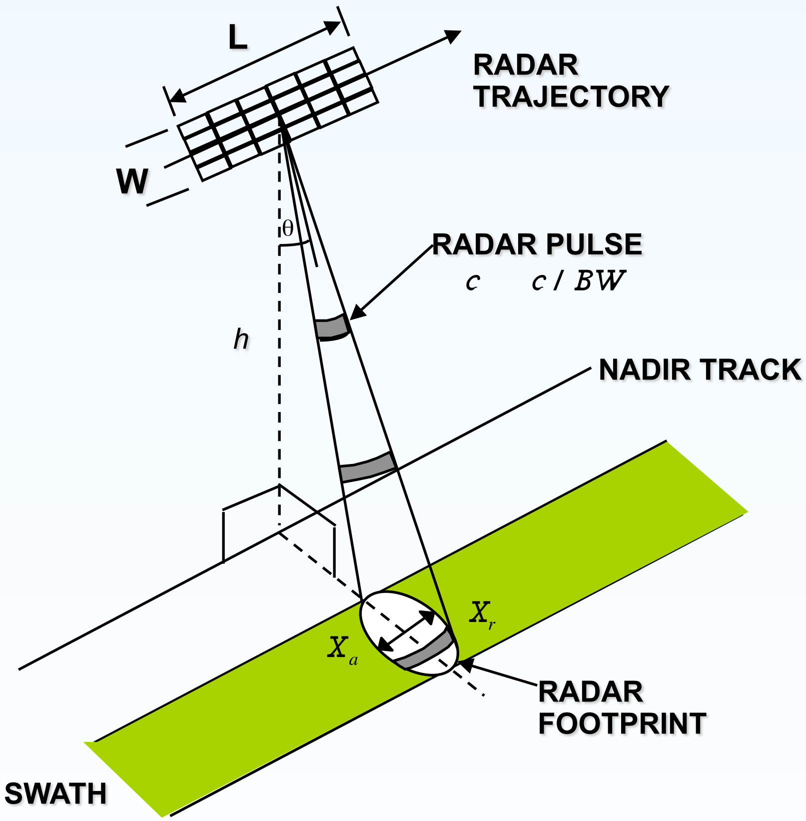
But it should be noted that:
- penetration depth is also related to the moisture of the target;
- microwaves do not penetrate water more than a few millimeters.

Radar imaging systems: ***how do they work?***

LandSAT image (optical)	ERS-1 image (SAR)
	

Radar imaging systems: Azimuth resolution

Azimuth resolution describes the ability of an imaging radar to separate two closely spaced scatterers in the direction parallel to the motion vector of the sensor



When two objects are in the radar beam simultaneously, for almost all pulses, they both cause reflections, and their echoes will be received at the same time. However, the reflected echo from the third object will not be received until the radar moves forward. When the third object is illuminated, the first two objects are no longer illuminated, thus the echo from this object will be recorded separately. For a real aperture radar, two targets in the azimuth or along-track resolution can be separated only if the distance between them is larger than the radar beamwidth.

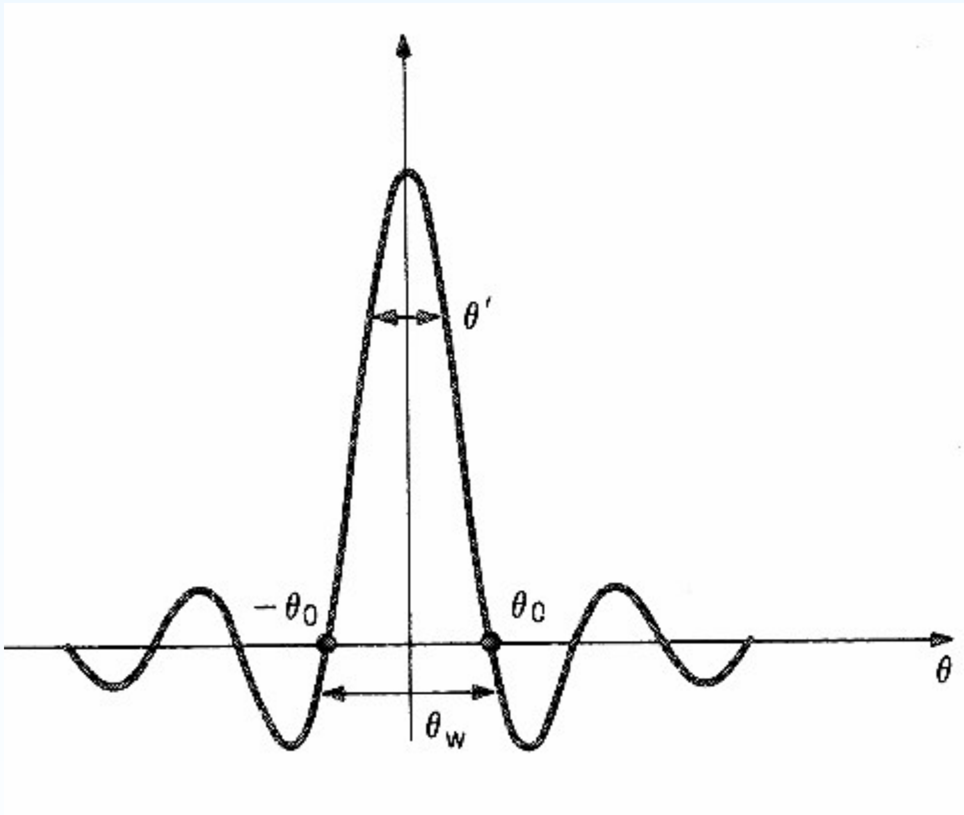
For all types of radars, the beamwidth is a constant angular value with range.

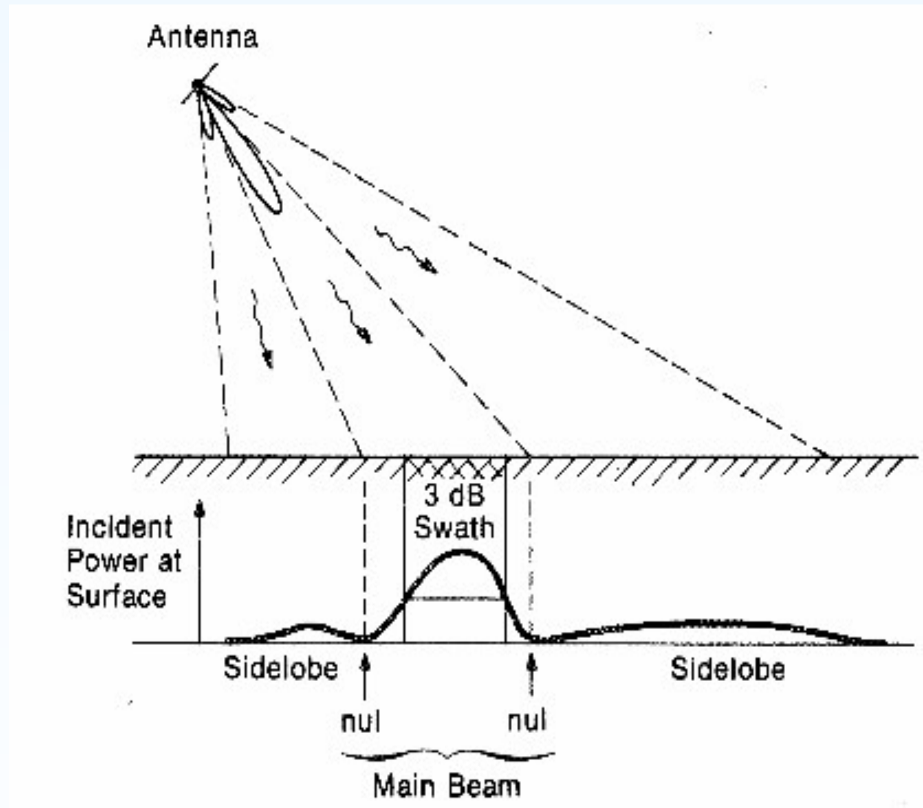
For a given radar wavelength, the azimuth beamwidth depends on the physical length of the antenna in the horizontal direction according to:

Beamwidth:

Radar imaging systems: Azimuth resolution

Field amplitude pattern for uniformly illuminated antenna

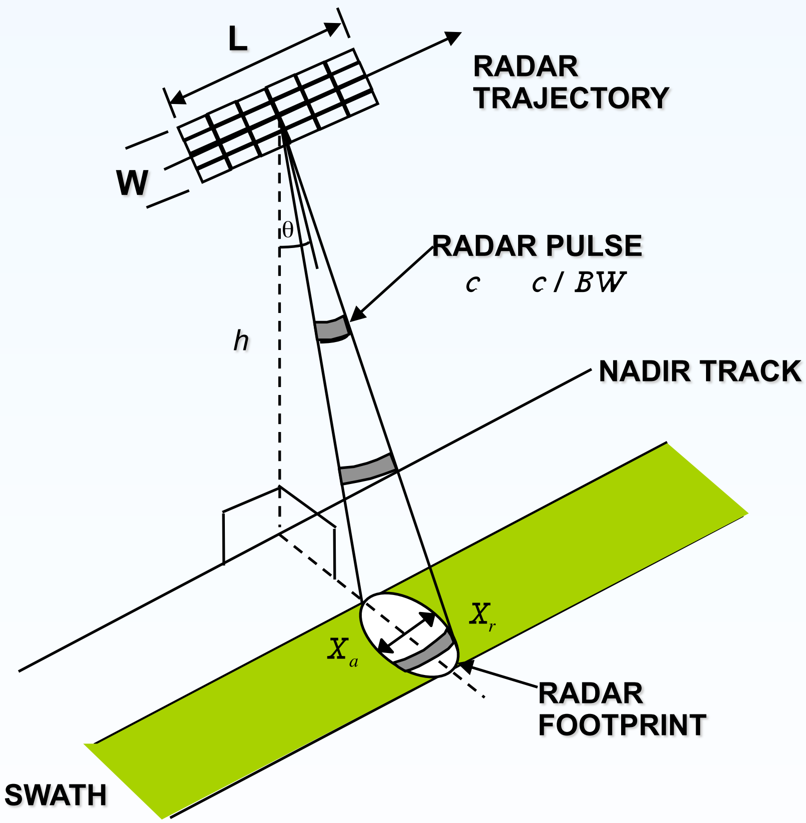




Radar imaging systems: Azimuth resolution

Real Aperture Radars have azimuth resolution determined by the antenna beamwidth, so that it is proportional to the distance between the radar and the target (slant-range). For real aperture radars, azimuth resolution can be improved only by **longer antenna** or **shorter wavelength**.

The use of shorter wavelength generally leads to a higher cloud and atmospheric attenuation, reducing the all-weather capability of imaging radars.

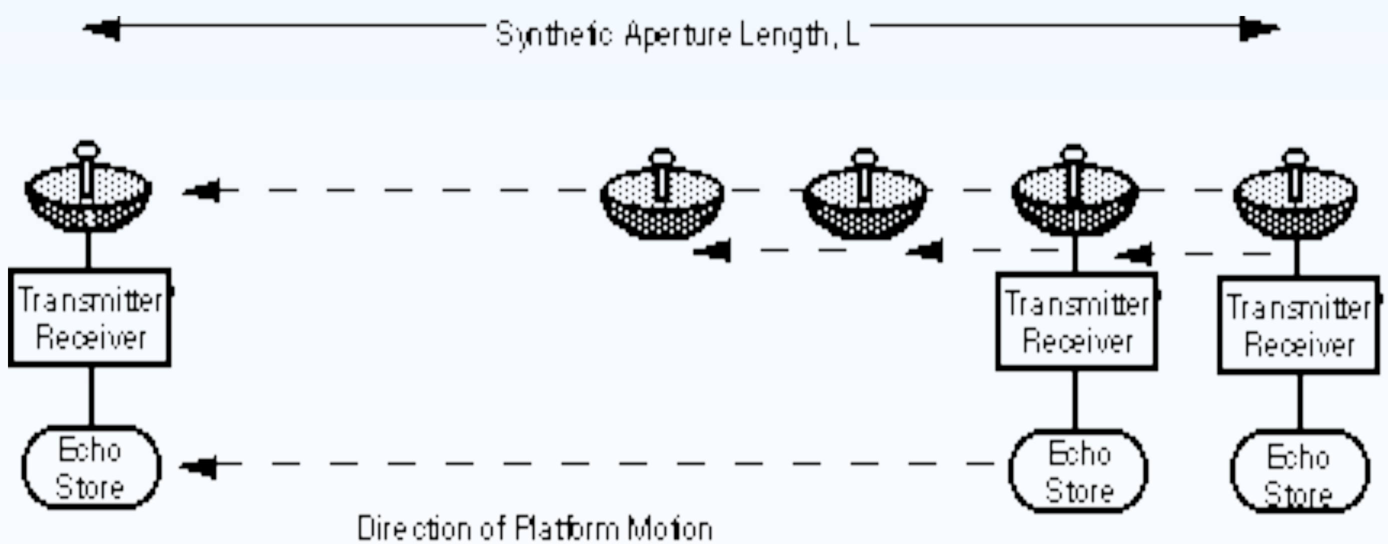


Beamwidth:

Azimuth resolution: $X_a \quad \frac{h}{L\cos}$

Radar imaging systems: ***Improving azimuth resolution***

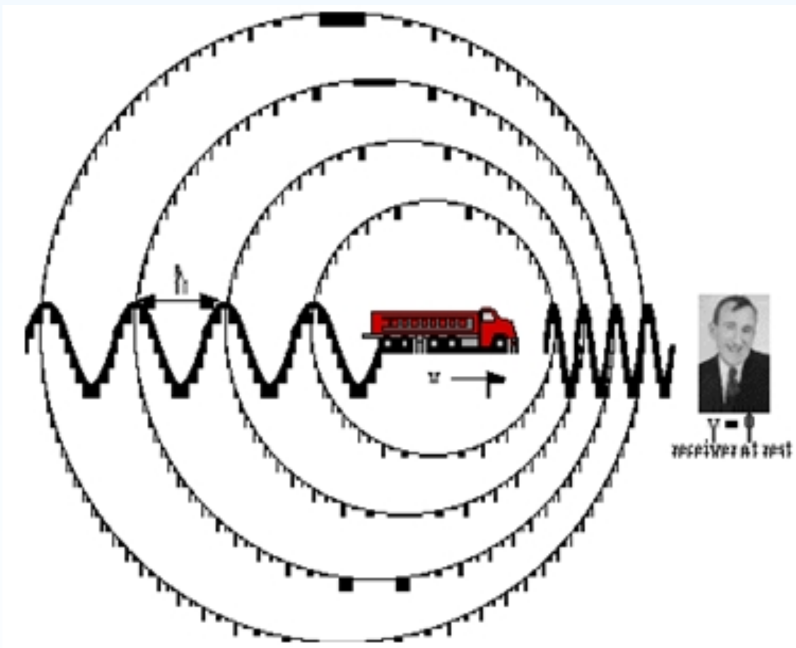
Synthetic Aperture Radar (SAR) refers to a technique used to synthesize a very long antenna by combining signals (echoes) received by the radar as it moves along its flight track.

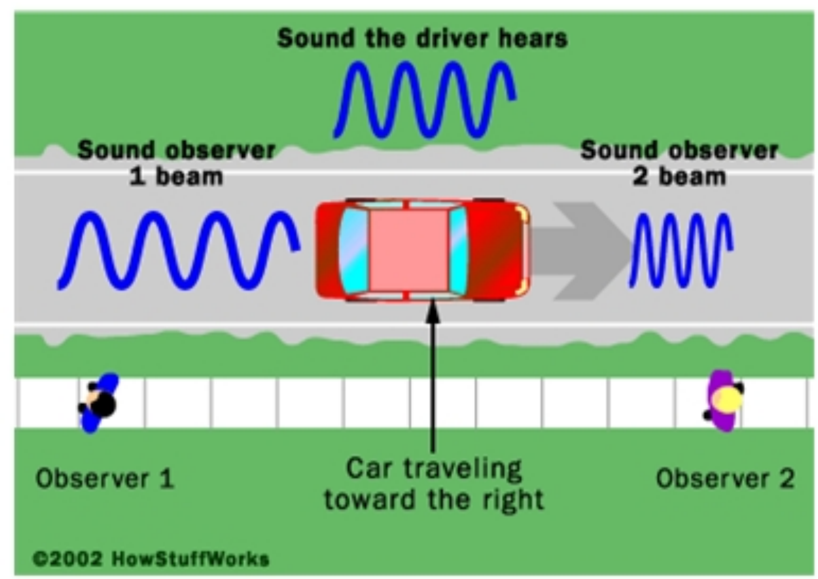


it is important to note that some details of the structure of the echoes produced by a given target change during the time the radar passes by. This change is explained also by the Doppler effect which among others is used to focus the signals in the azimuth processor.

Radar imaging systems: Improving azimuth resolution

Perception is relative!
It's to do with the effect of sound or light waves on the person seeing or hearing them - like the difference you hear as an emergency siren passes you. It is caused by the change in distance between the thing creating the wave and whatever is measuring, seeing or hearing the wave.





Radar imaging systems: Improving azimuth resolution

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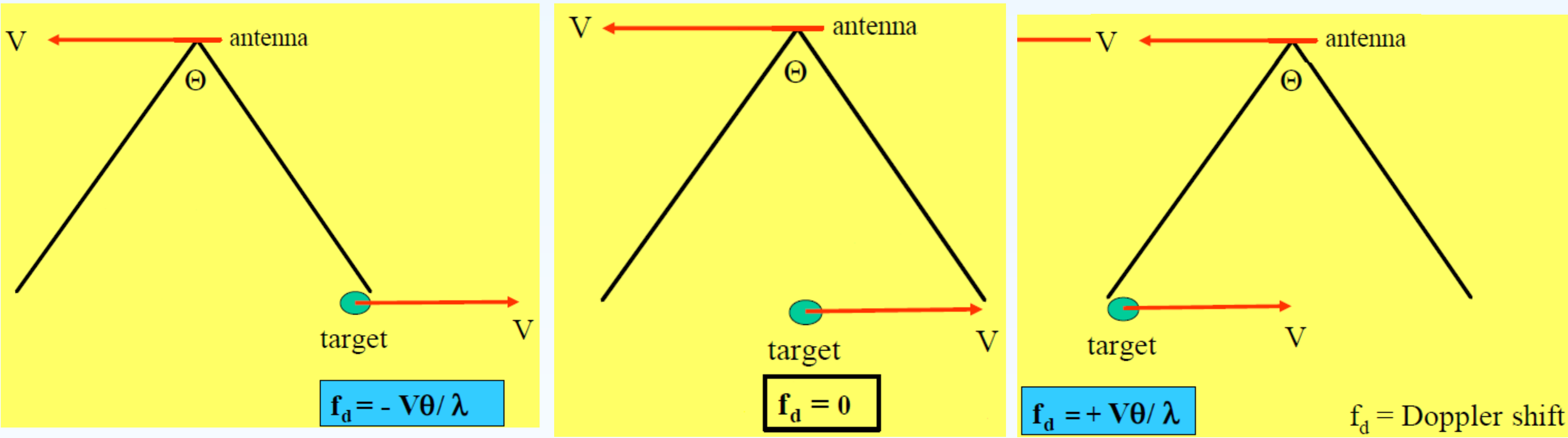


The Azimutal bandwith of the SAR is B = 2 f_d

The time interval that can be resolved is

$\Delta t = 1/B = 1/2f_d = \lambda/2V\theta = D/2V$ (because of $\theta = \lambda/D$).

The spatial interval in flight direction that can be resolved =azimuthal resolution = $X_a = V\Delta t = D/2$.

Synthetic Aperture Radars: *Improving azimuth resolution*

The accuracy for determining the position of a target in the antenna beam is better, the longer one is able to listen to the sound signal.

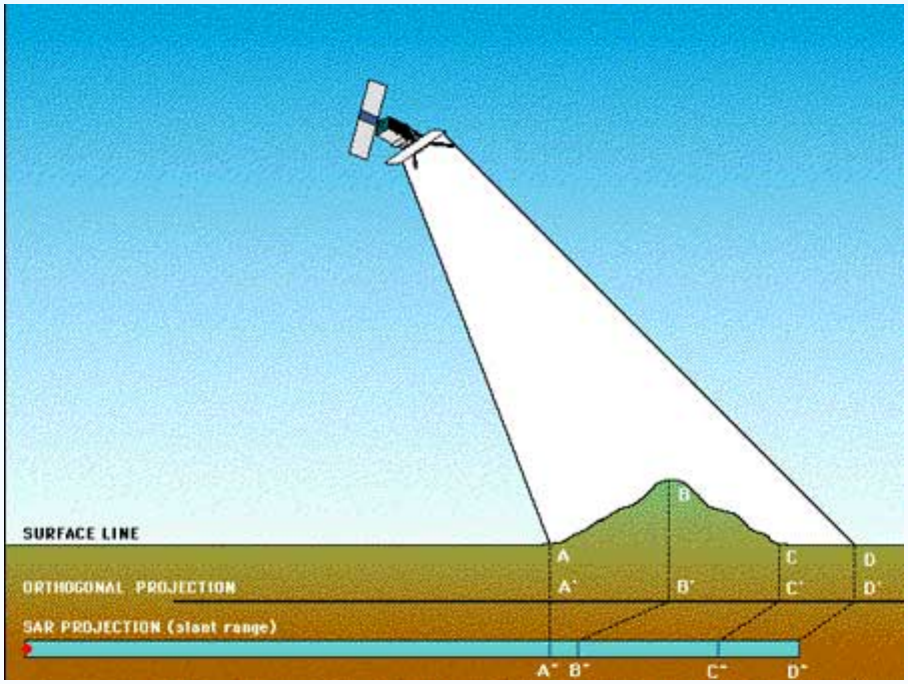
- The larger the beamwidth, the longer one can listen to the sound
- The smaller the antenna, the larger is the beamwidth ($\beta = \lambda/D$)
- Thus, the azimuthal resolution becomes better, the smaller the antenna length D.

This result is completely contrary to what applies to other remote sensing instruments where the larger the antenna, the better the resolution.

Here, the smaller the antenna, the better the resolution.
Azimuth resolution is $X_a = D/2$

The azimuthal resolution of a SAR is **independent of range R** and is **proportional to D**

Radar imaging systems: ***Range resolution***



The most striking feature in SAR images is the "strange" geometry in range direction.

This effect is caused by the SAR imaging principle: measuring signal travel time and not angles as optical systems do. The time delay between the radar echoes received from two different points determines their distance in the image.

Let us consider the mountain as sketched in the figure. Points A, B and C are equally spaced when vertically projected on the ground (as it is done in conventional cartography). However, the distance between A'' and B'' is considerably shorter compared to B'' - C'', because the top of the mountain is relatively close to the SAR sensor This effect is called "foreshortening". It is, among other effects, the most common geometric distortion in SAR images. Foreshortening is obvious in mountaineous areas, where the mountains seem to "lean" towards the sensor .

Radar imaging systems: ***Range resolution***

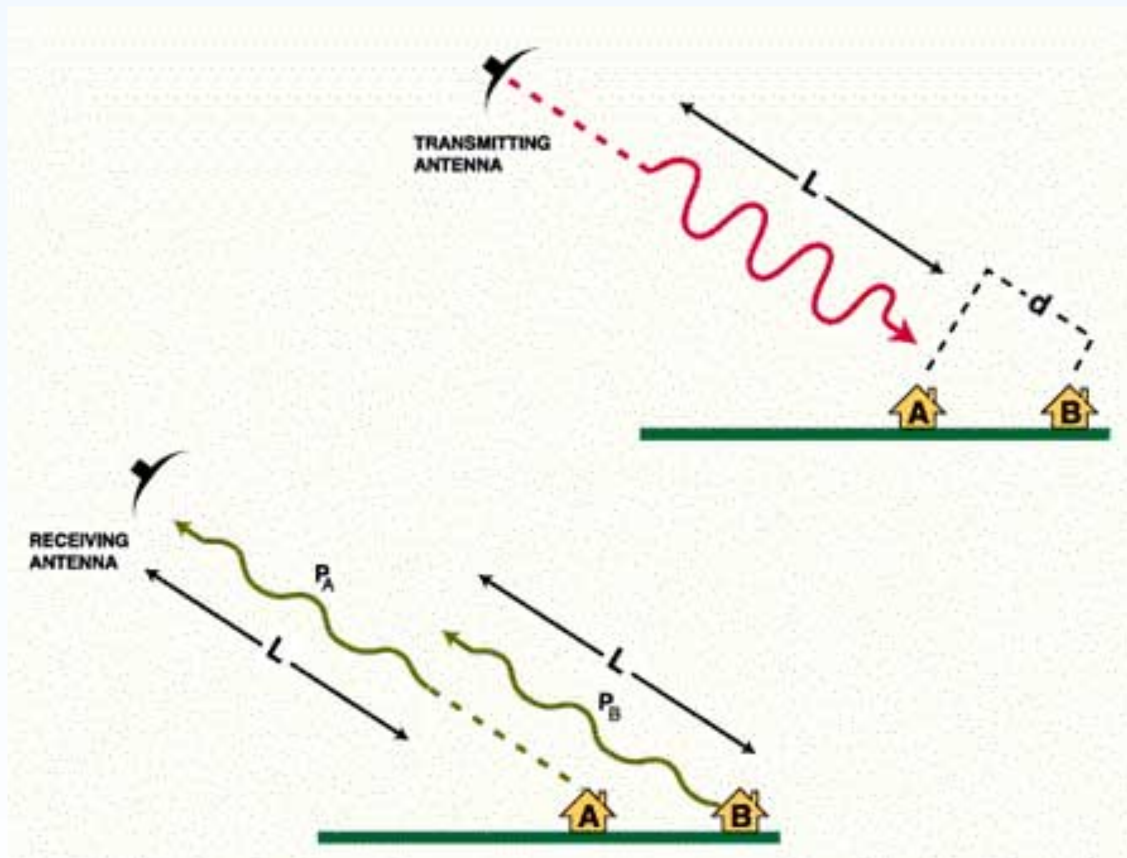
On a flat surface , to distinguish between two targets, the backscatter must
be received at two different times. Since the radar pulse must travel two ways, the two targets lead to distinguished echoes if:
d > L/2

If d==L/2, A and B are mapped as same target !

Range resolution
(here B = bandwith, Θ = radar incidence angle

$$X_r = \frac{c\,\tau}{2\sin\theta} = \frac{c}{2B\sin\theta}$$

Good range resolution for
- short pulse
- Large incidence angle



Radar imaging systems: Range resolution

To improve range resolution, radar pulses should be as short as possible. However, it is also necessary for the pulses to transmit enough energy to enable the detection of the reflected signals.

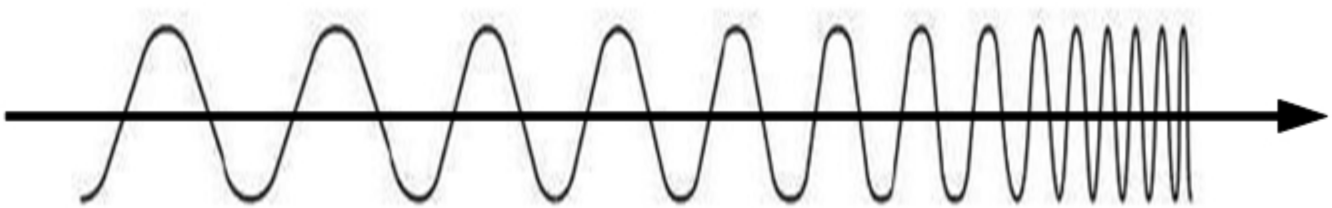
If the pulse is shortened, its amplitude must be increased to keep the same total energy in the pulse.

One limitation is the fact that the equipment required to transmit a very short, high-energy pulse is difficult to build.

Synthetic Aperture Radars were developed as a means of overcoming the limitations of real aperture radars.

Synthetic Aperture Radars: Improving range resolution

Pulse chirping: Signal modulation is a way to increase the radar pulse length without decreasing the radar range resolution



This technique is analogous to the technique used in the azimuth (flight) direction to improve the azimuthal resolution.

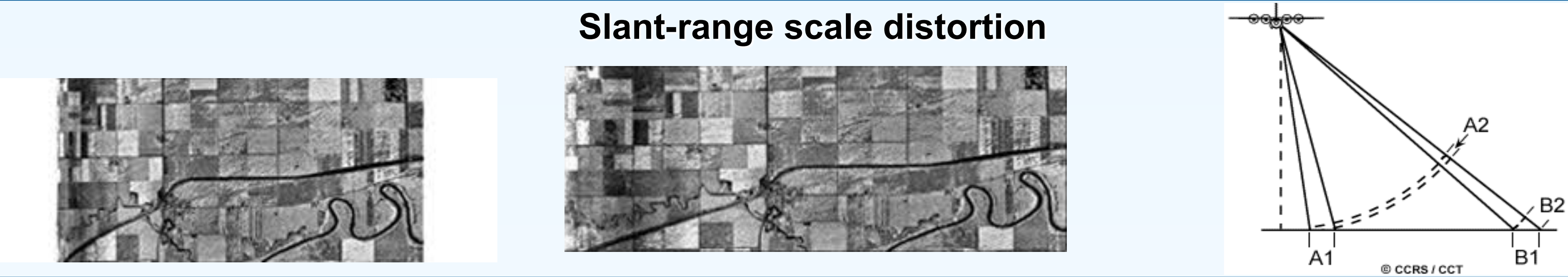
In the **azimuth direction** the frequency modulation of the backscatter signal results from the **motion of the platform** and is thus naturally induced.

In **range direction,** the frequency modulation of the backscatter signal is **artificiallyinduced by the emitted signal**

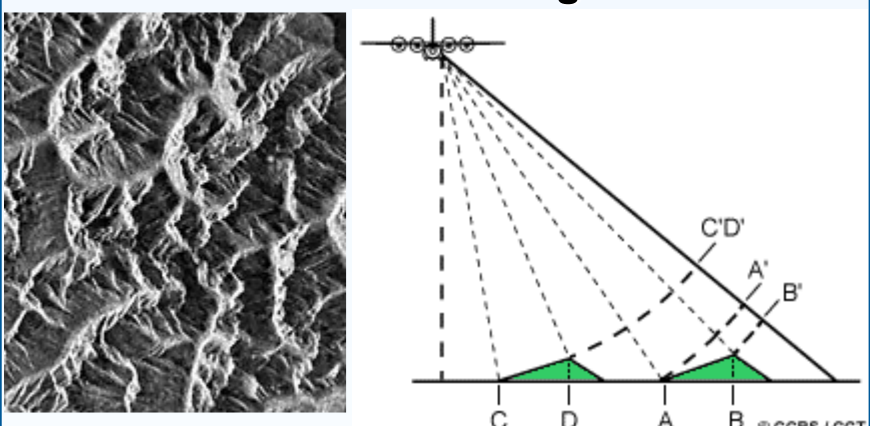
All civilian spaceborne SARs, and most civilian airborne SARs use linear FM chirps as the modulation scheme.

Synthetic Aperture Radars: *data processing*

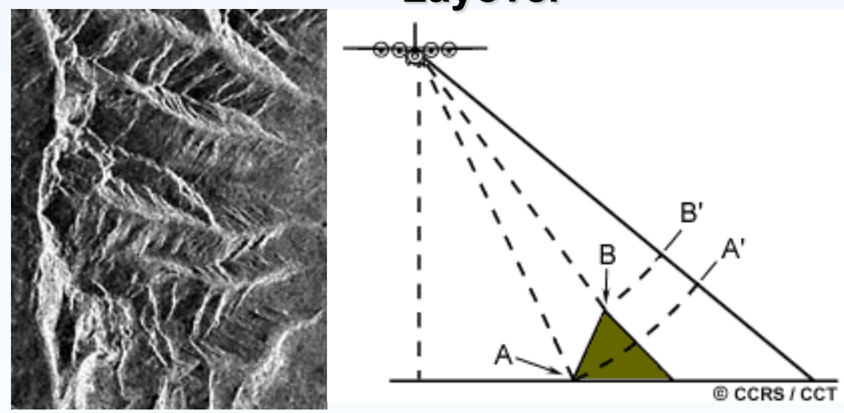
Slant-range scale distortion



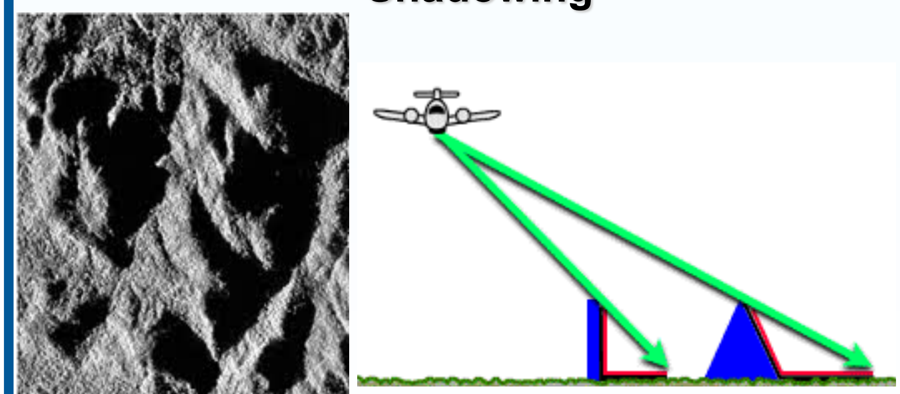
Foreshortening



Layover

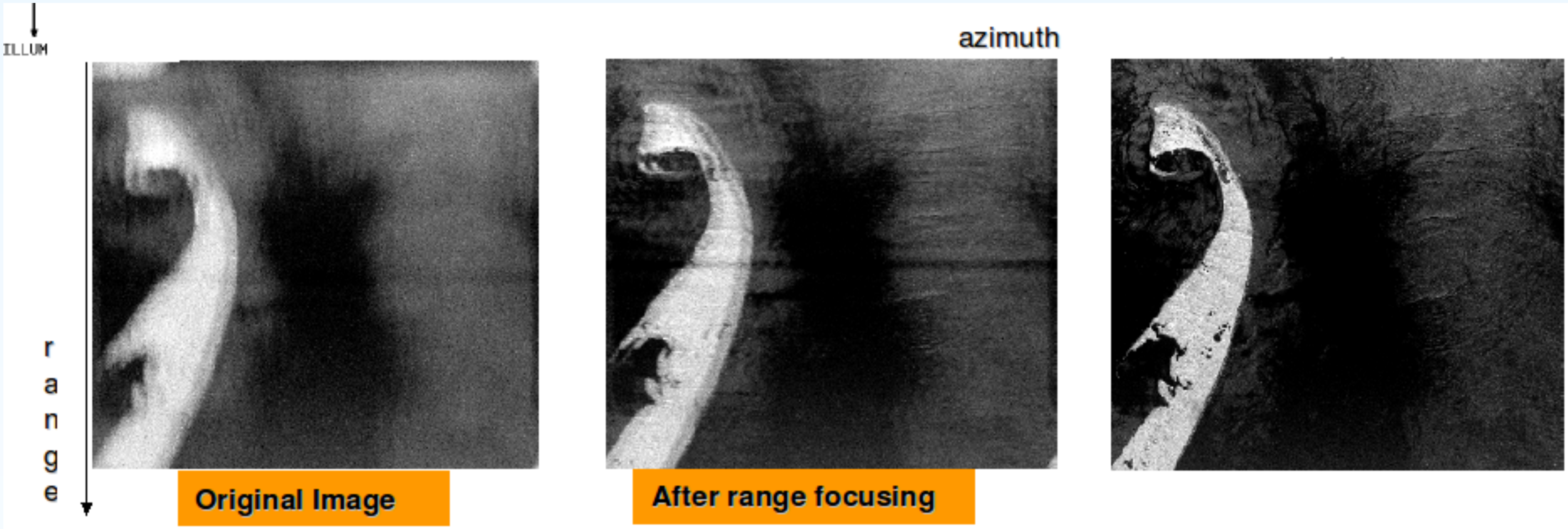


Shadowing



These effect my enhance the visual appearance of relief and terrain structure, making radar imagery excellent for applications such as topographic mapping and identifying geologic structure

Radar imaging systems: ***Data processing***



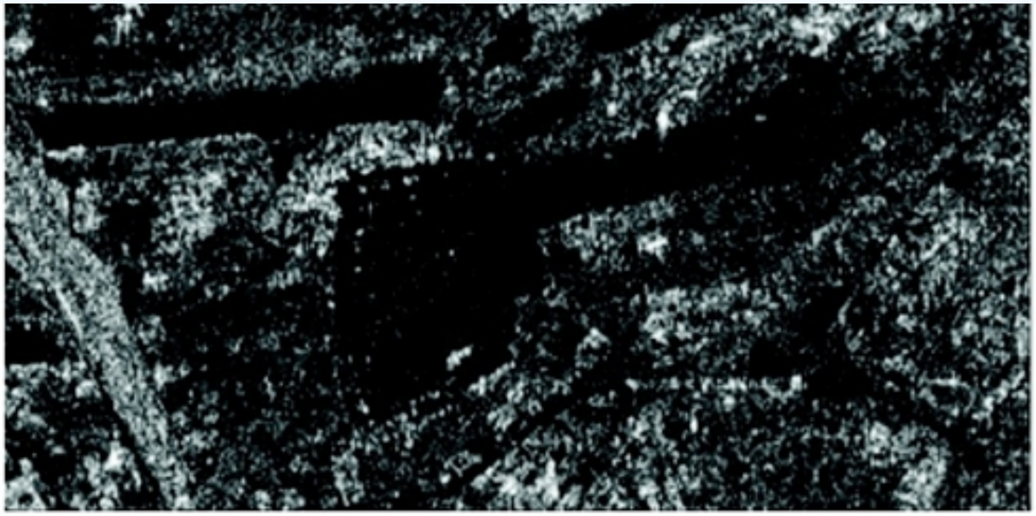
For even moderate azimuth resolutions, a target's range to each location on the synthetic aperture changes along the synthetic aperture. The energy reflected from the target must be "mathematically focused" to compensate for the range dependence across the aperture prior to image formation.

SAR processing can be considered as a two-dimensional focusing operation :

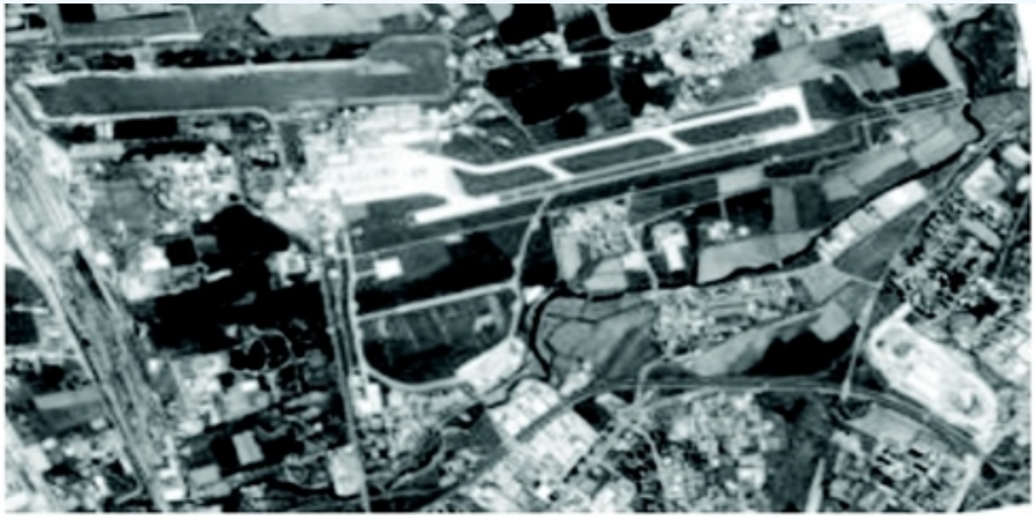
- Range focusing: relatively straight forward
- Azimuth focusing: depends upon the Doppler histories produced by each point in the target field

Synthetic Aperture Radars: Data processing

Speckle in SAR

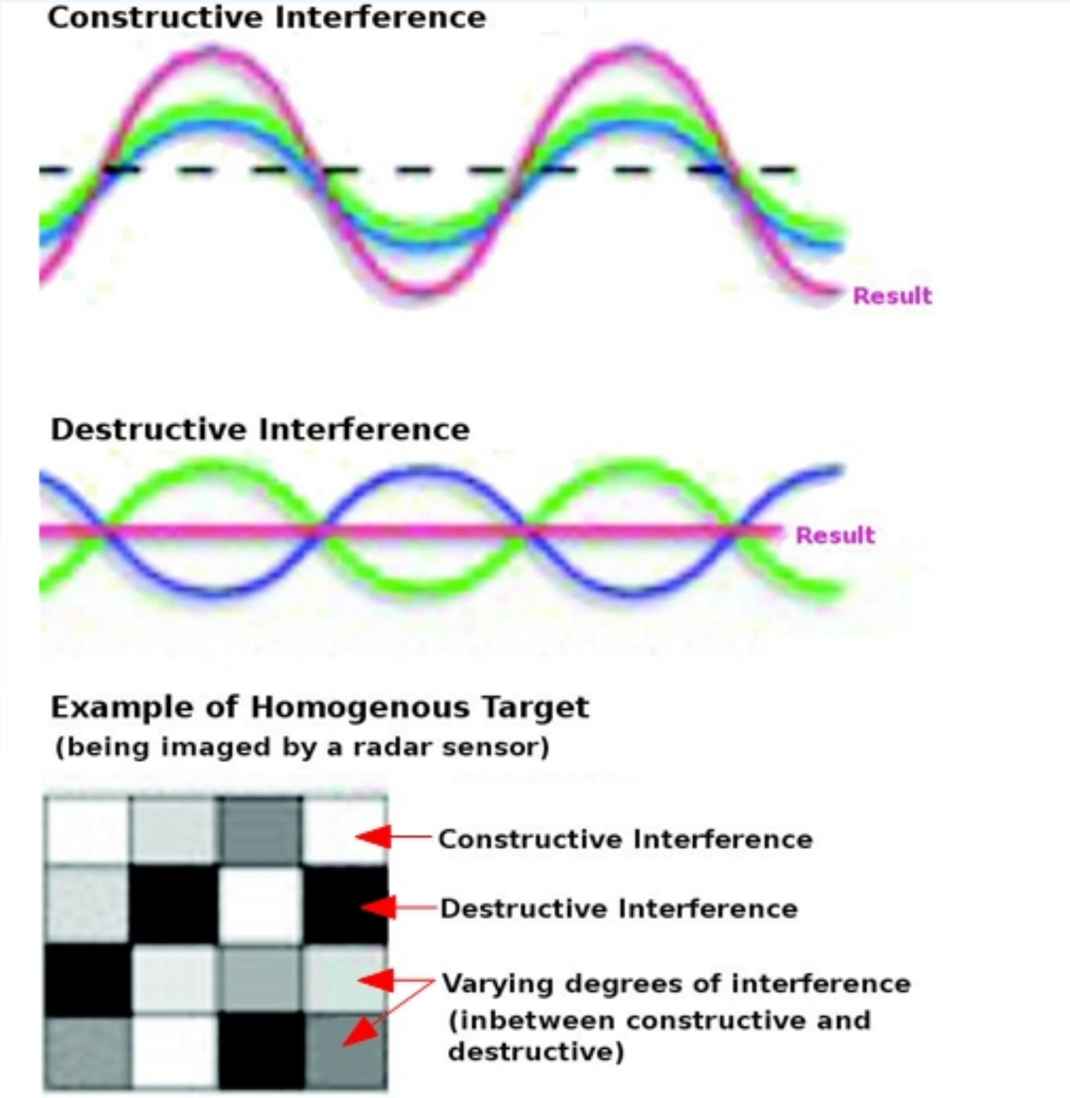


SAR image



optical image

Synthetic Aperture Radars: Data processing



Contribution from random scattering elements on the surface, with varying path length to antenna cause constructive / destructive interference.

Therefore amplitude is the sum of the coherent contributions with random phase shifts.

Unlike system noise, speckle is a real electromagnetic measurement.

Correct using:

- multi-look processing
- spatial filtering.

Synthetic Aperture Radars: Conclusions

- SAR simulates a very long antenna using the **"synthetic aperture principle"**. The "synthetic" antenna is generated by the motion of the platform (aircraft or satellite) and through the use of signal processing of the Doppler shift associated with the motion of the aircraft

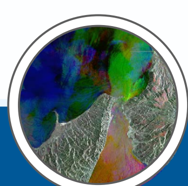
- As a result SAR resolution is **independent of the platform height and proportional to the synthetic antenna length.**

- For Envisat SAR (called ASAR), the length of the synthetic antenna is **~20 km**

- Generally, depending on the processing, resolutions achieved are of the order of 1-2 metres for airborne radars and 5-50 metres for spaceborne radars.

- SAR processing requires **very heavy computing** after data acquisition



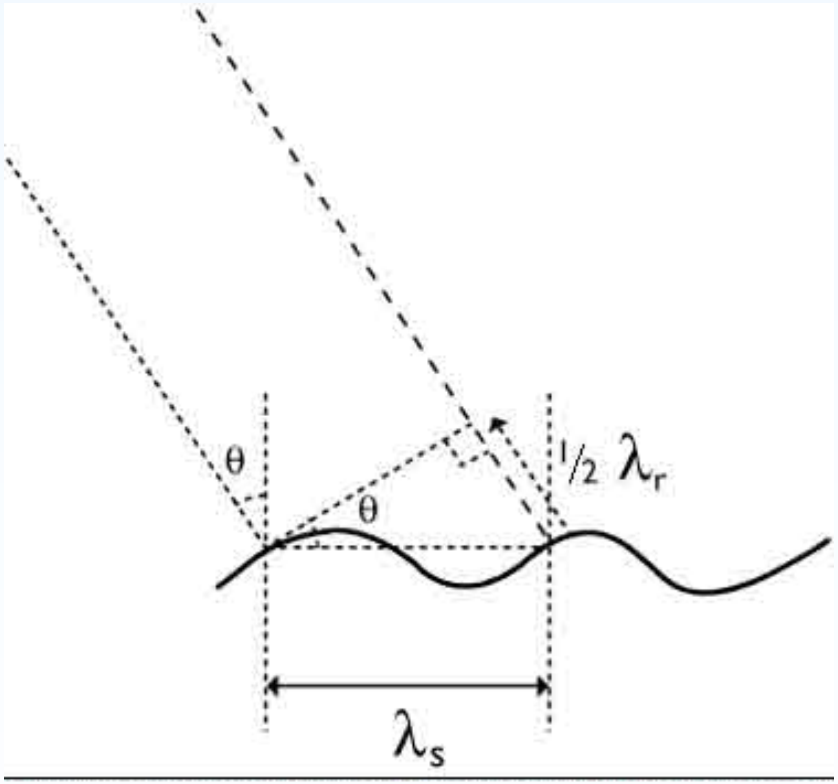


Synthetic Aperture Radars: Observing the ocean

At the ocean's surface radar echoes from SARs are reflected through **Bragg Scatering**

Bragg scattering is the strong, resonant signal for surface roughness (waves) on the scale of the radar wavelength

The short Bragg-scale waves are formed in response to wind stress (need at least 3.25m/sec at C band).



$$\lambda_s = \frac{\lambda_r}{2\sin\theta}$$

where:

λ_r radar wavelength

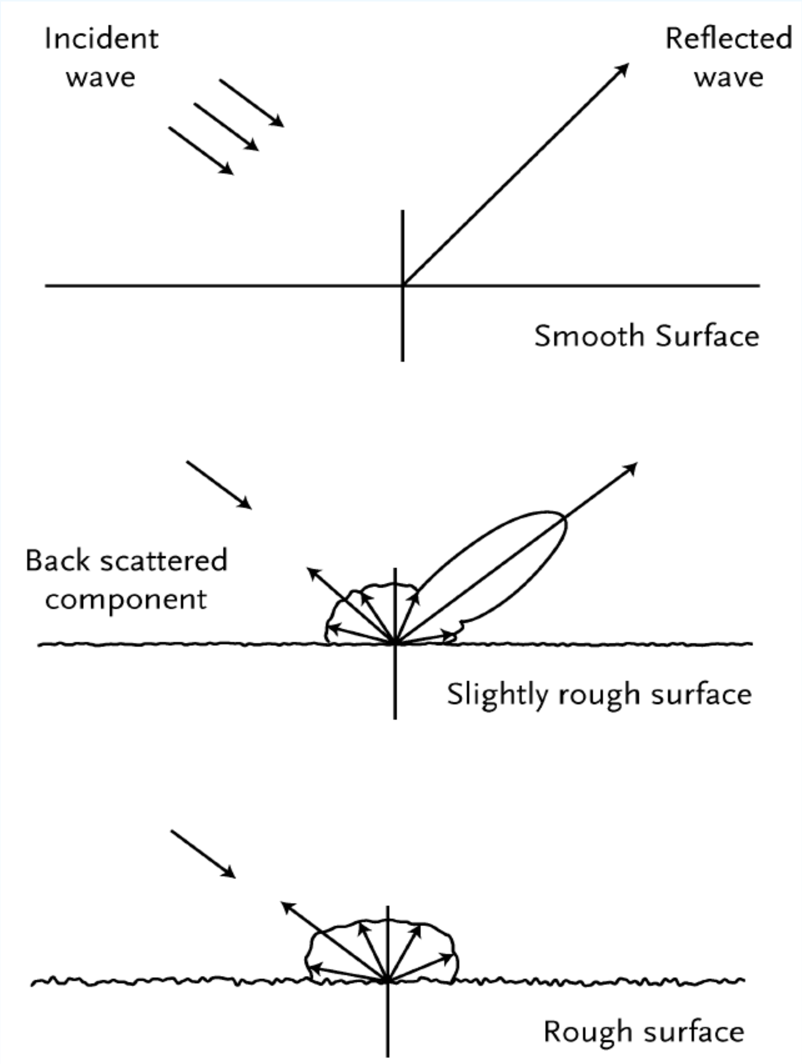
λ_s sea surface wavelenght

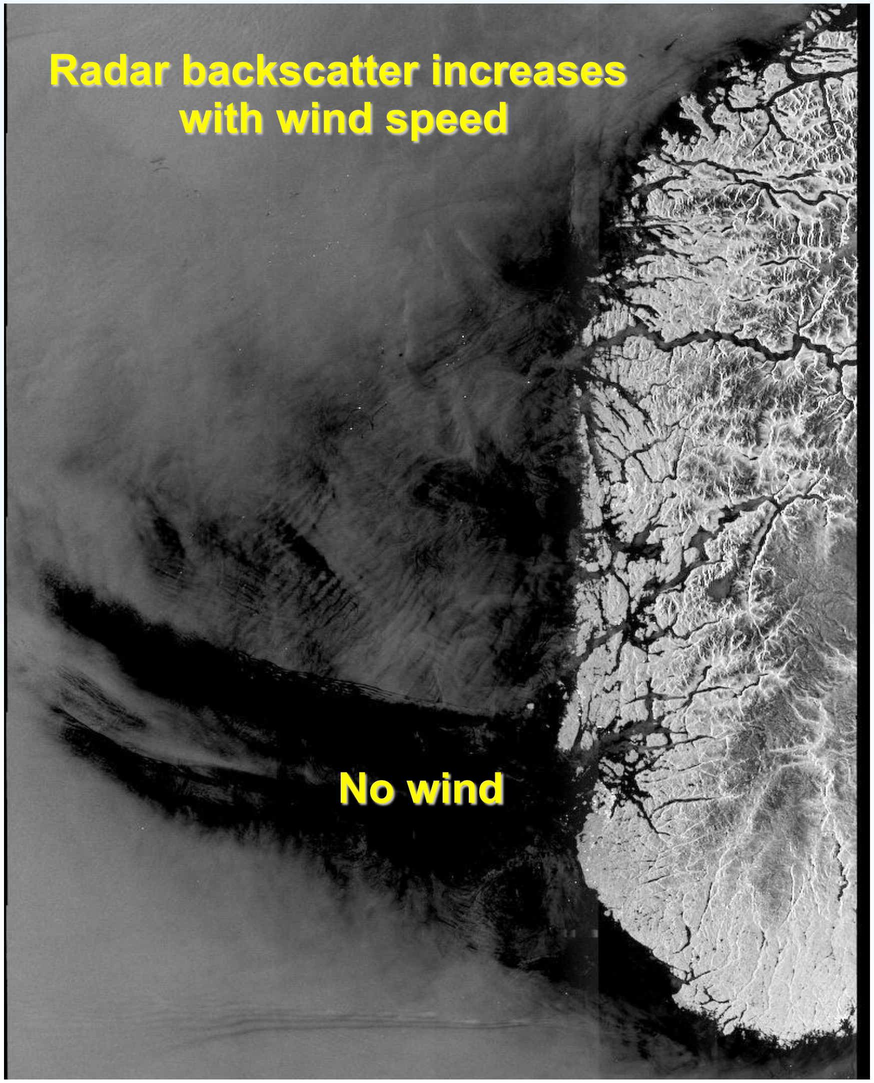
θ incidence angle

For C-band, $\lambda_r \sim 6$ cm

Synthetic Aperture Radars: Observing the ocean

Bragg scattering is **affected by wind**



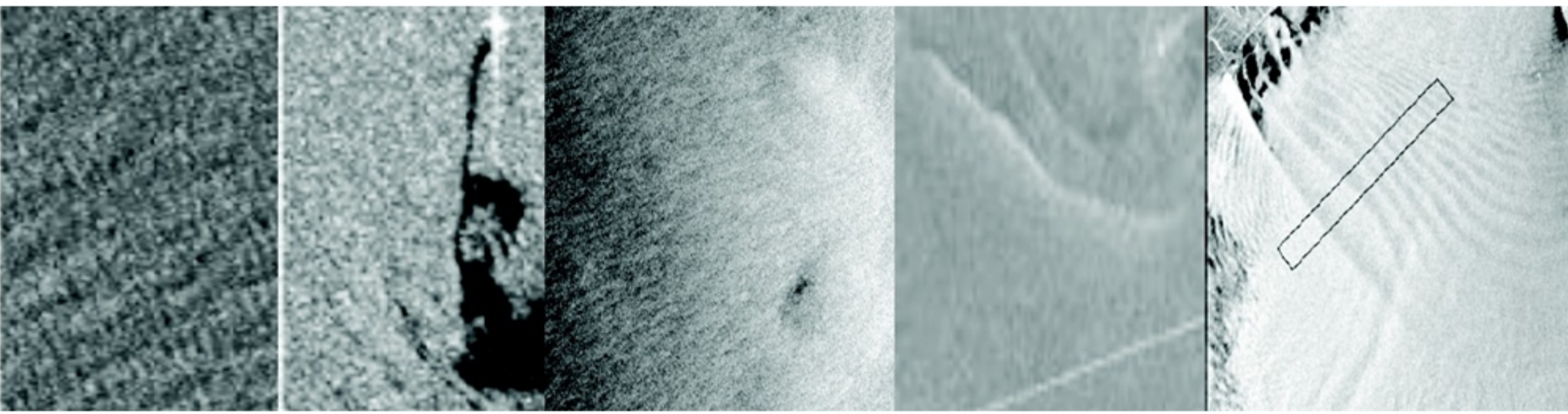


Bragg scattering is affected by wind **and many other things ...**

Synthetic Aperture Radars: Observing the ocean

- SAR measures **sea surface roughness** (Bragg waves - order cm)
- Sea surface roughness is affected by **wind**, **waves**, **currents**, **surface film** (oil / biological matter) or sea ice
- Backscatter from the surface roughness is registered by SAR in both amplitude and phase

Waves | Oil spill | Wind field | Current front | Internal waves

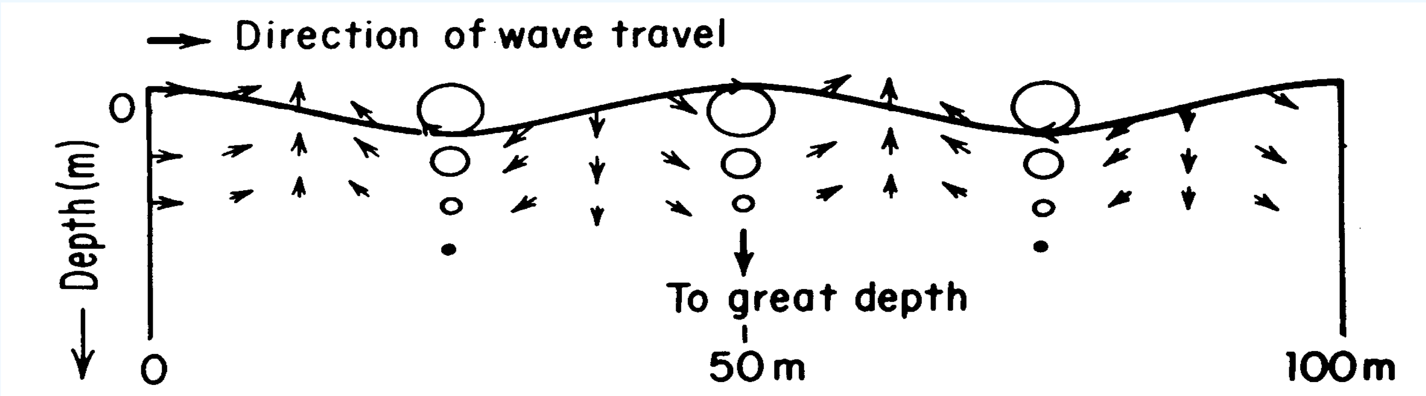


Synthetic Aperture Radars: Observing the ocean

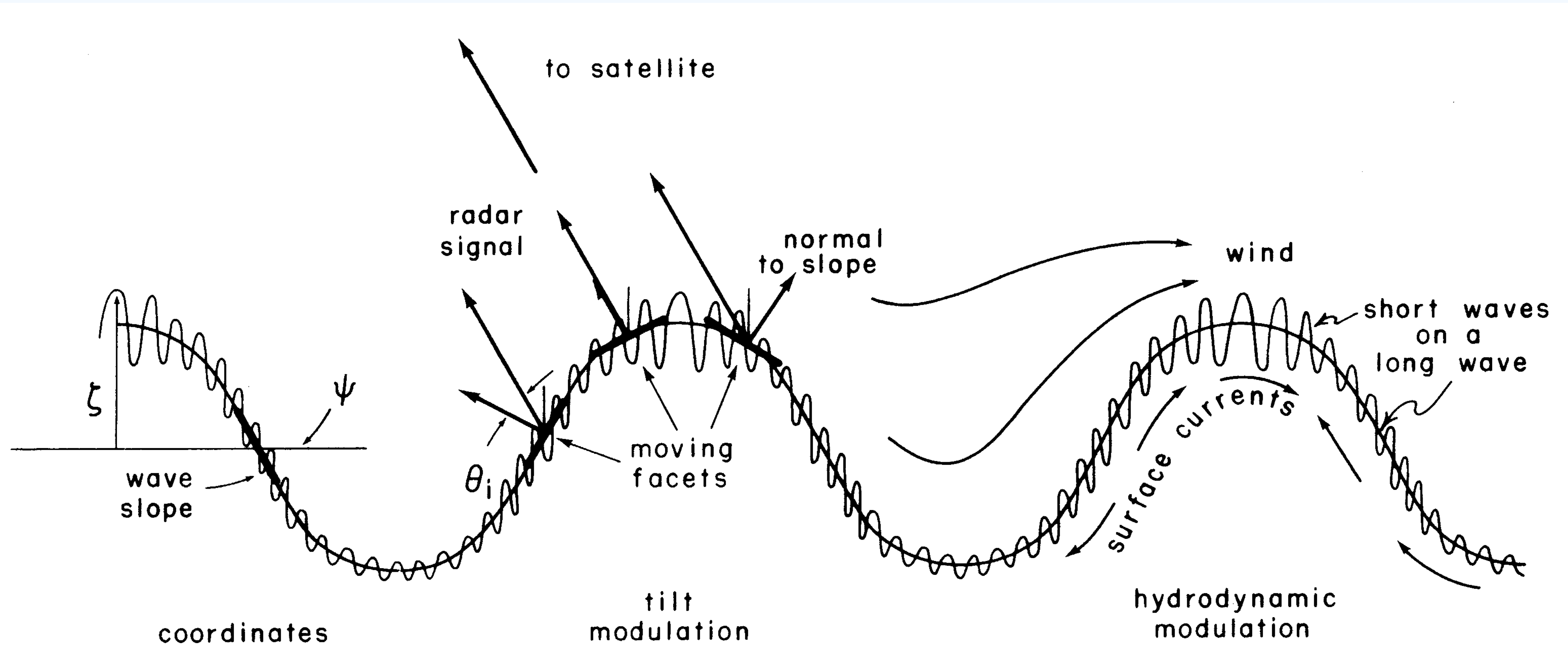
Bragg Scattering is modulated by three principal mechanisms that can enhance or suppress average backscatter of ocean surface:

- **Tilt modulation**: change in local incident angle
- **Hydrodynamic modulation**: alteration of Bragg scale waves due to surface currents
- **Damping by surfactants**: suppression of Bragg scale waves

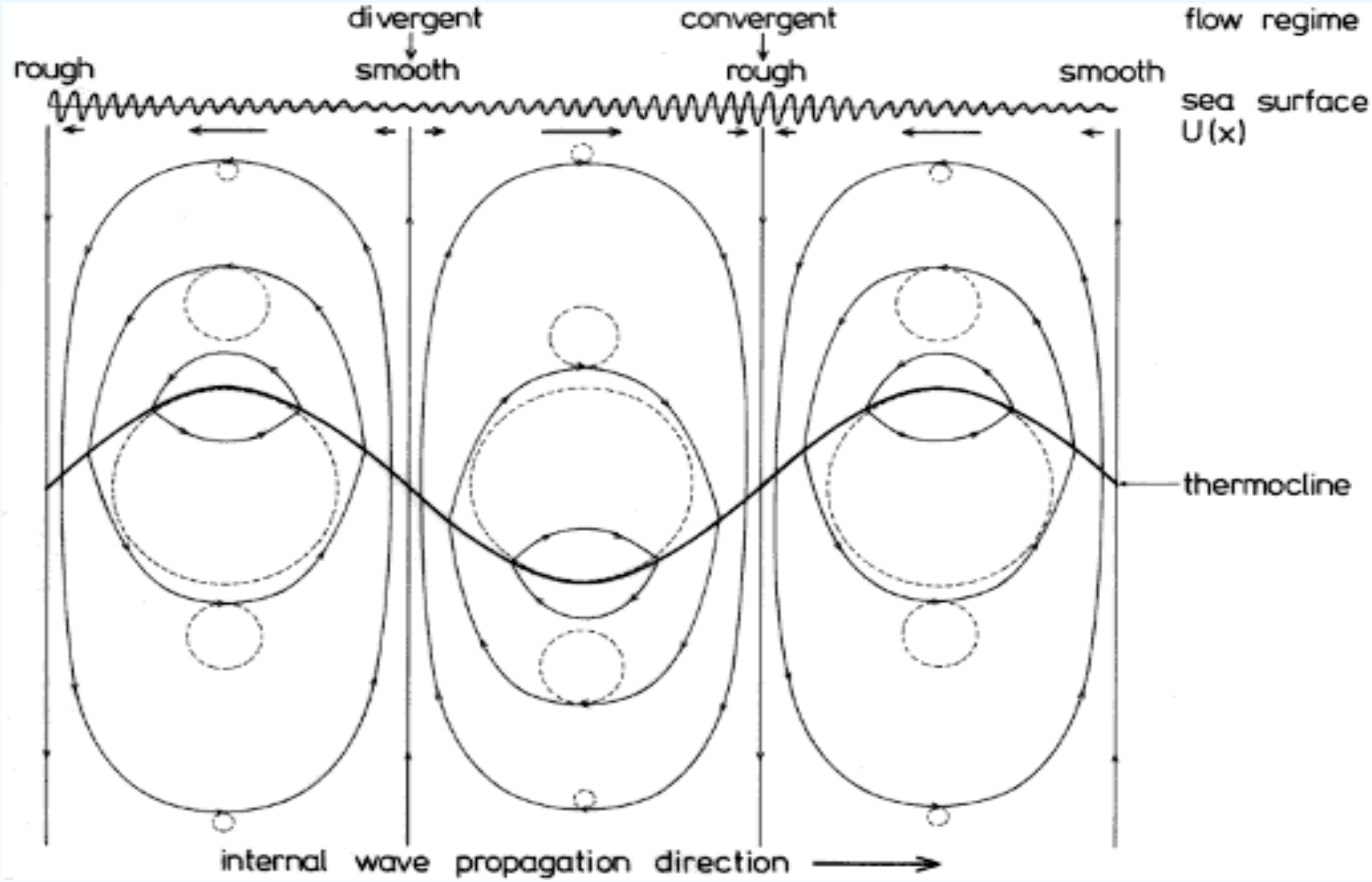
Synthetic Aperture Radars: Observing the ocean



Long waves change the slope of the small Bragg waves, with maximum backscatter on the face of the wave, 90° out of phase with the wave amplitude.



Synthetic Aperture Radars: Observing the ocean



Schematic plot of processes associated with the passage of a linear oceanic internal wave. Deformation of the thermocline (heavy solid line), orbital motions of the water particles (dashed lines), streamlines of the velocity field (light solid lines), surface current velocity vectors (arrows in the upper part of the image), and variation of the amplitude of the Bragg waves (wavy line at the top). [After Alpers, 1985]

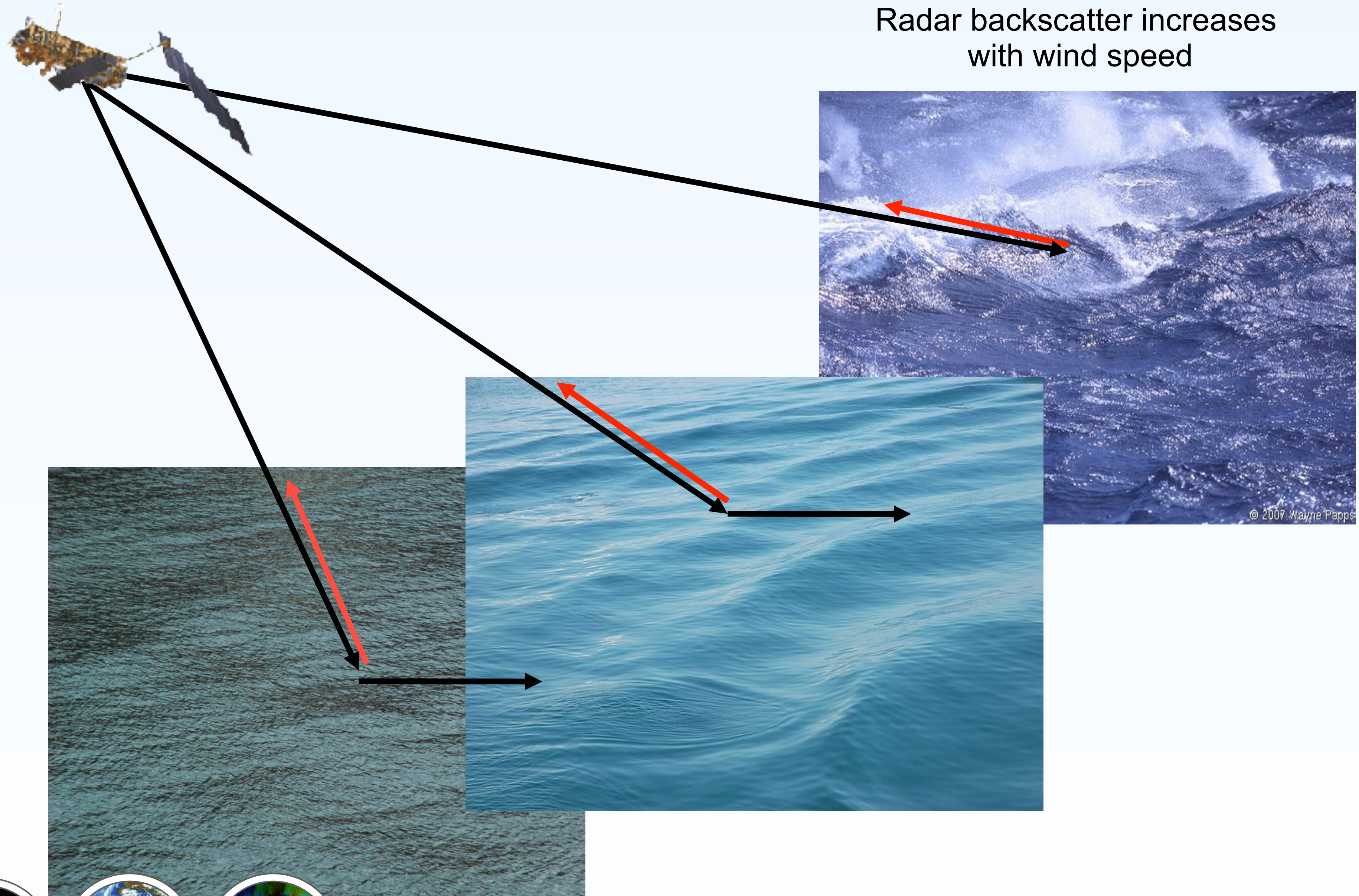
Synthetic Aperture Radars: Observing the ocean

An Additional influence on ocean backscatter is “Velocity Bunching”

- Artifact of SAR system
- Caused by moving ocean surface
- Moving waves introduce Doppler offsets and result in azimuth displacement ‘errors’ in images
- Displacements can combine in non-linear fashion and cannot be removed
- Most prevalent for azimuth travelling waves

Velocity bunching does not change average backscatter; it introduces only local variations due to location displacements

Synthetic Aperture Radars: Wind measurements



Synthetic Aperture Radars: Wind measurements

Backscatter σ depends on:

- wind speed
- wind direction relative to radar look direction
- radar incidence angle (known)

One measurement of σ gives several possible solutions of wind speed and direction

For SAR, information about wind direction is needed as auxiliary information

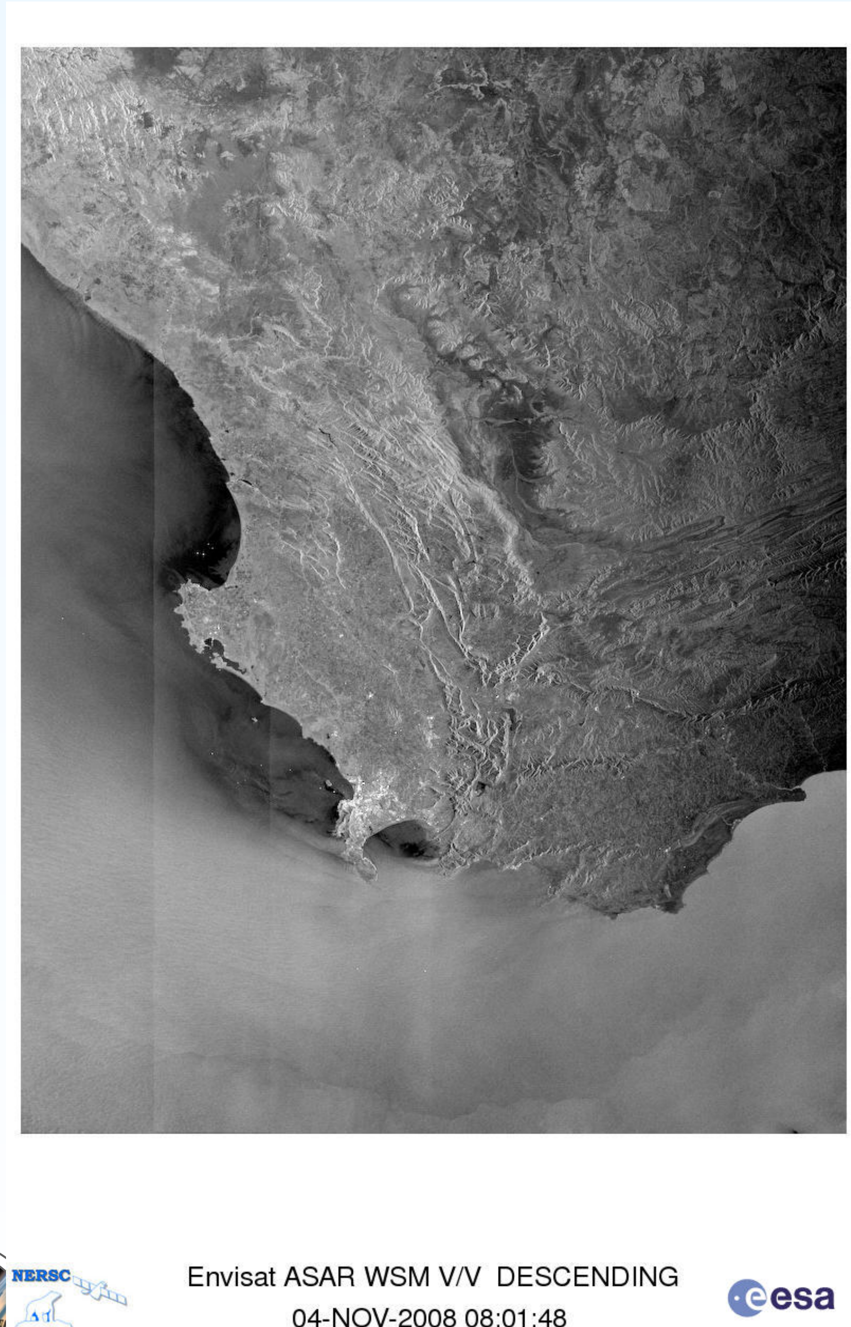
- Simplest solution is to take wind direction from numerical model
- Scatterometer (if colocated in time and space)
- Use wind streaks in the SAR-image

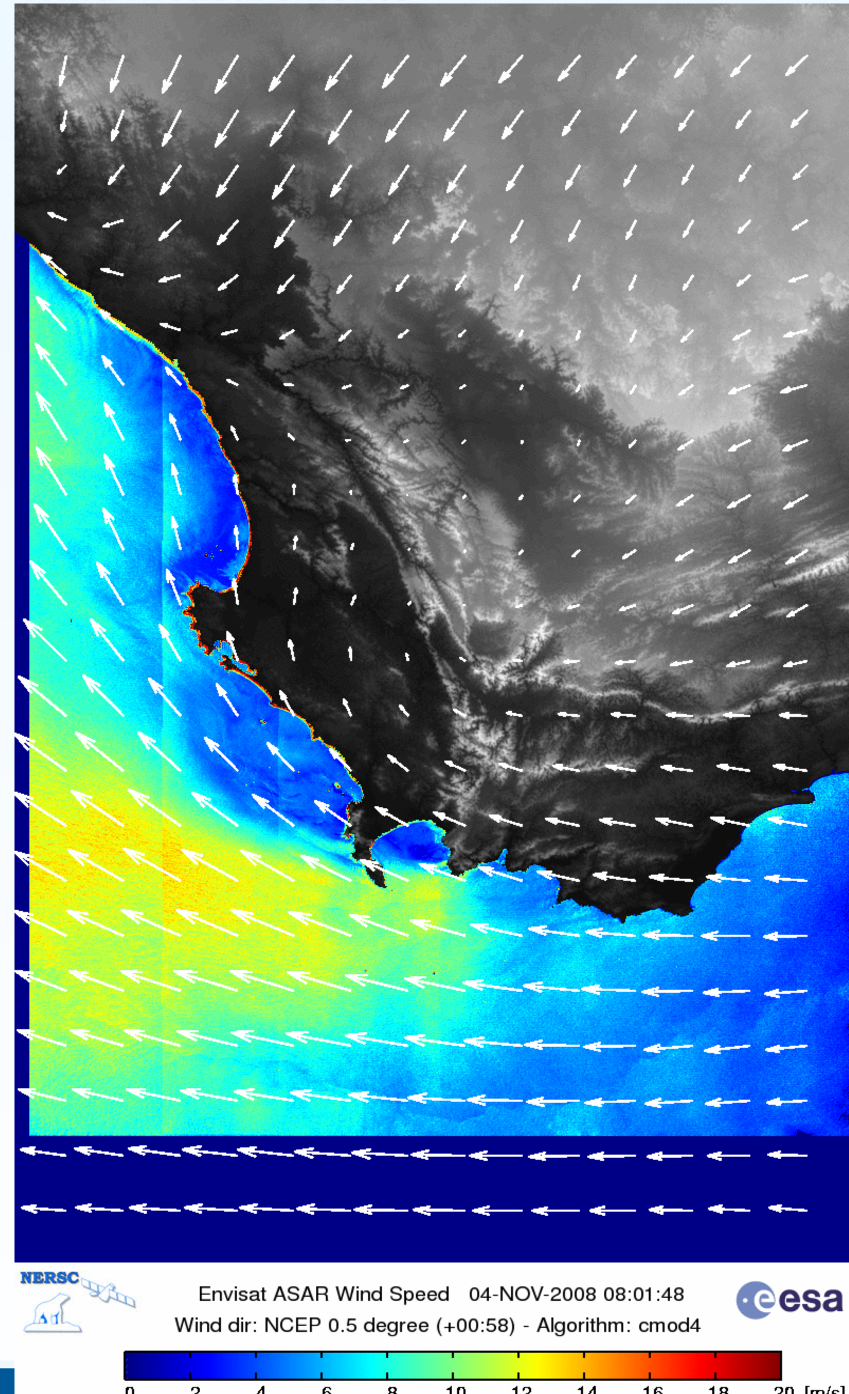
Empirical functions are then used to relate σ to wind speeds These functions are tuned to co-located

- ECMWF 10 m winds
- ERS-1 scatterometer data (σ)

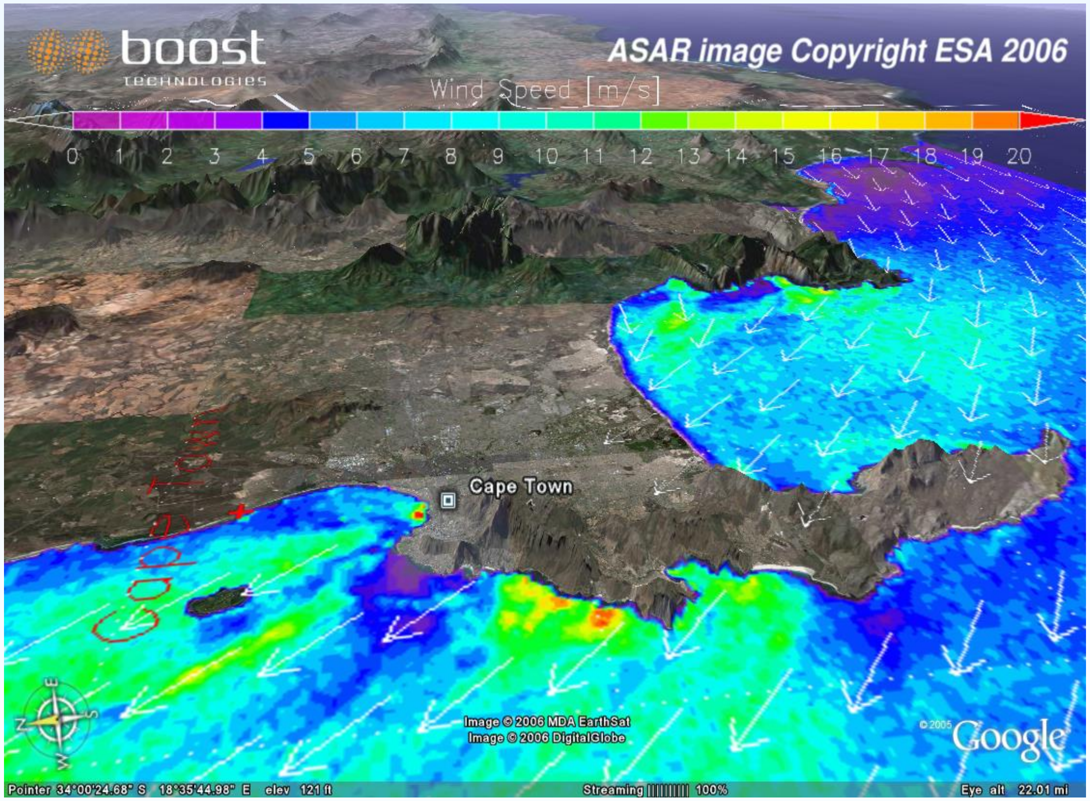
CMOD-algorithm (C-band model function), with same algorithm later applied to SAR

Synthetic Aperture Radars: Wind measurements





Synthetic Aperture Radars: *Wind measurements*



SAR provides unique opportunity to monitor oceans winds at high resolution
(typically 1 km x 1 km)

Available information and performance

- Wind speed accuracy: < 2 m/s (rms)
- Wind direction accuracy: ~25° (rms)

Applications

Near real-time:

- High resolution coastal wind field measurement
- Improve Oil spill monitoring
- Coastal navigation

Long term:

- Wind farm design, wind resource assessment.
- Understanding coastal dynamics
- Monitoring and study of meteorological phenomena

Synthetic Aperture Radars: Wave measurements

Wave fields, wave / current interactions

Synthetic Aperture Radars: *Wave measurements*

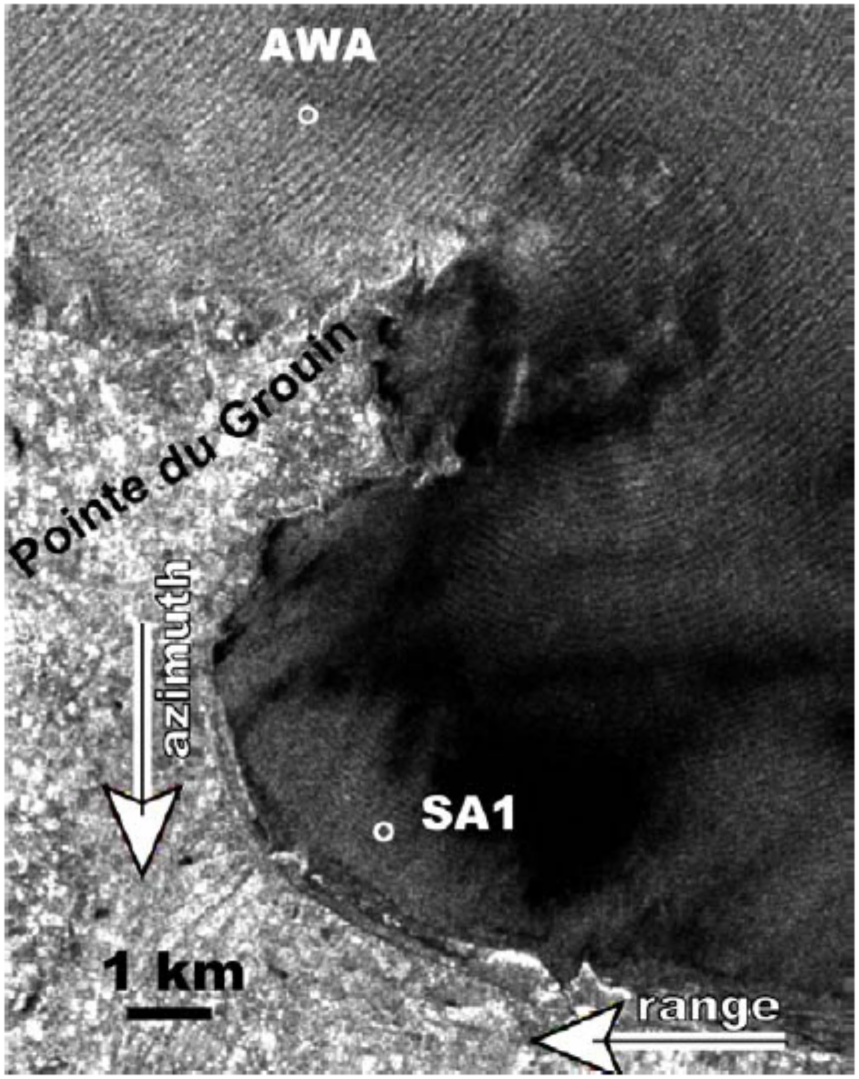


Fig. 1. Excerpt of the image acquired by ENVISAT on March 9 2003 at 21h45. The position of two instruments is indicated (AWA and SA1). The dark areas correspond to regions of very weak winds. The refraction of waves around the Pointe du Grouin is clearly visible.

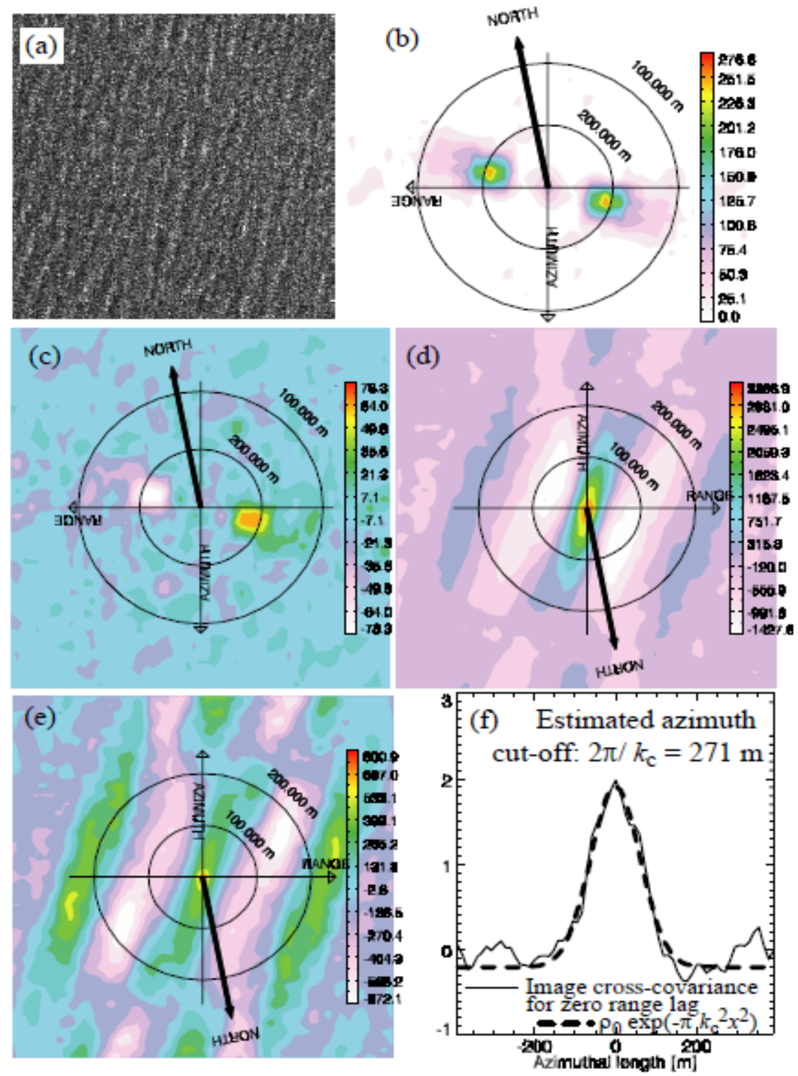


Fig. 2. Illustration of the steps in the wave spectra inversion for the imagette located near the DW1 instrument (Fig. 5). a) intensity image. b) image spectrum c) imaginary part of the image cross-spectrum used for direction ambiguity removal. d) autocovariance of the image e) Enhanced image autocovariance after removal of nonlinear contribution. f) Azimuth cutoff used for quasi-linear spectrum correction.

Collard, F., F. Ardhuin and B. Chapron (2005): Extraction of coastal ocean wave fields from SAR images. IEEE Journal of Oceanic Engineering, 30(3), 526–533.

Synthetic Aperture Radars: *Wave measurements*

Instruments:

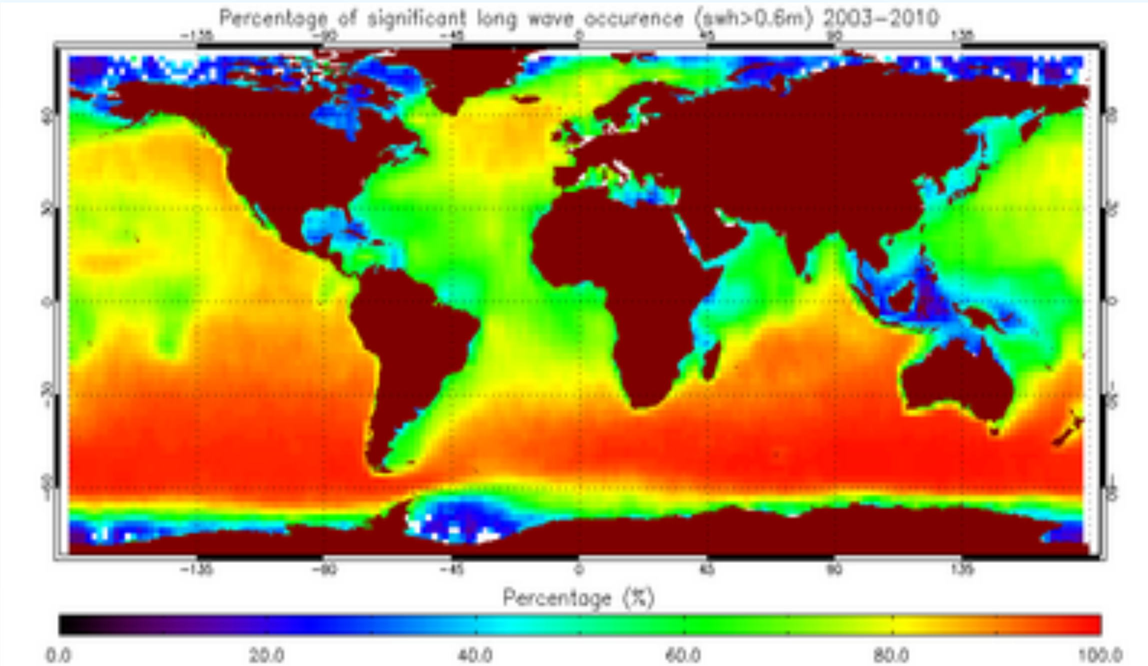
- SAR is the only spaceborne instrument that can measured the two-dimensional ocean wave spectra
- concept operationally since 1991 (ERS-1, ERS-2, Envisat).
- Envisat ASAR Wave Mode – improved successor of ERS Wave Mode
- Sentinel-1 (2011->) - improved successor of Envisat ASAR

Wave Applications:

- Wave nowcasting and wave forcasting: Assimilation into numerical wave models for better swell wave prediction
- Assessment of swell wave climate, globally
- Coastal wave studies, and coastal wave climate
- Swell tracking and storm location

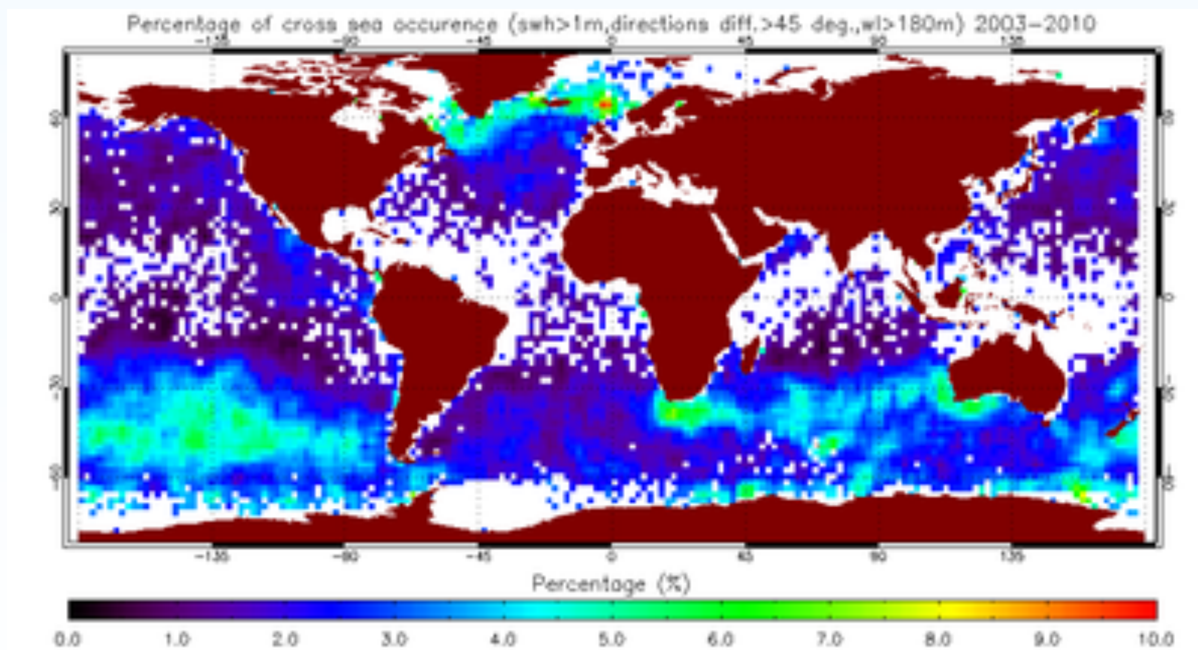
Example of application:
http://www.esa.int/esaEO/SEMAKIV681F_economy_0.html

Synthetic Aperture Radars: **Wave measurements**



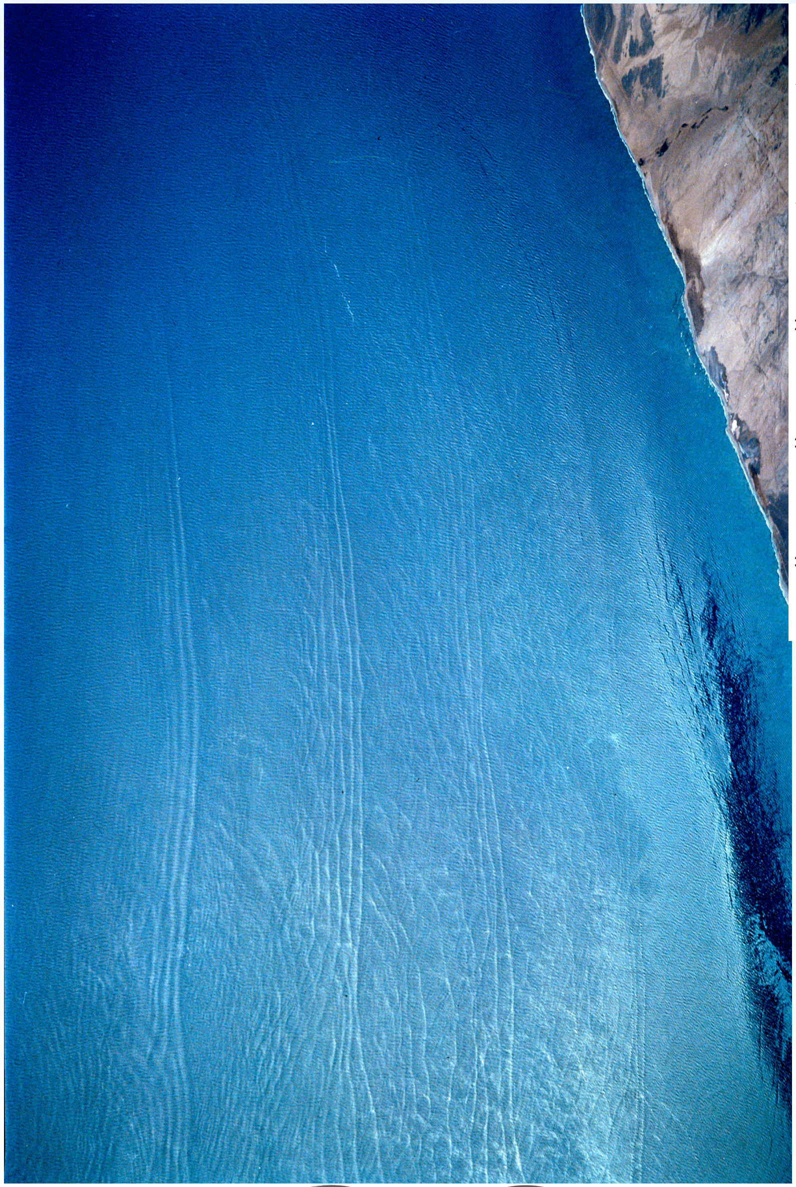
Agulhas Current region is unique. It is a region where most long waves and cross-seas occur.

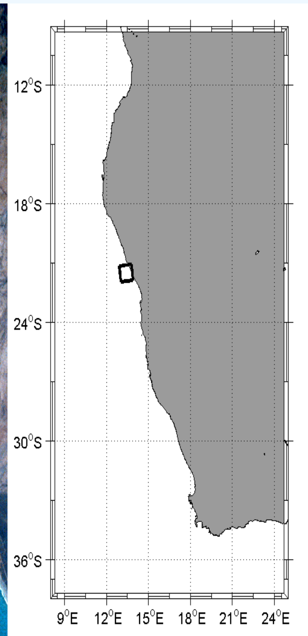
There is a high risk of Rogue wave and dangerous seas for ships.



Synthetic Aperture Radars: Internal Waves

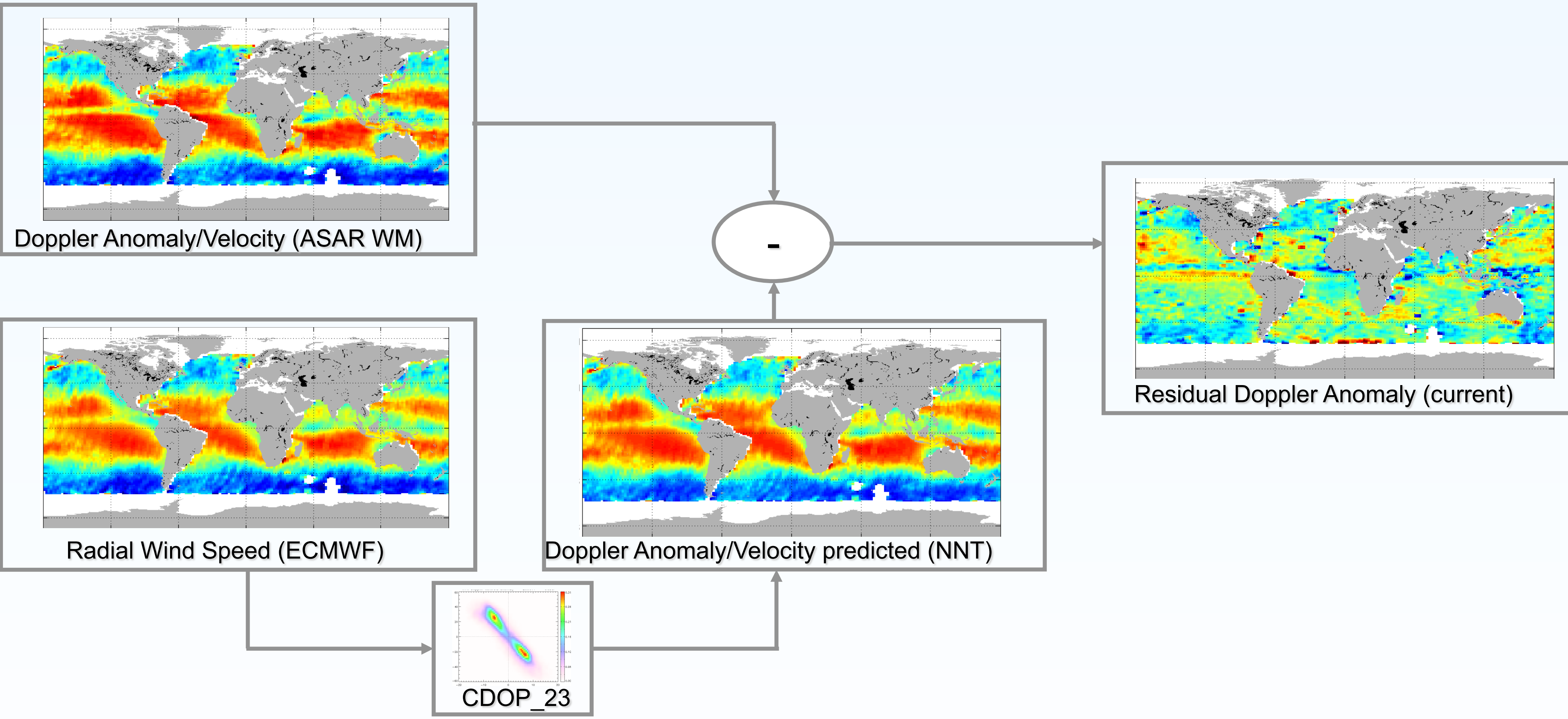
There are internal waves all around Africa





Synthetic Aperture Radars: Current measurements

Direct measurements of the surface current velocity across the track of the satellite are derived using Doppler Anomaly signal from ASAR



Slide from Dr. Fabrice Collard

Synthetic Aperture Radars: Current measurements

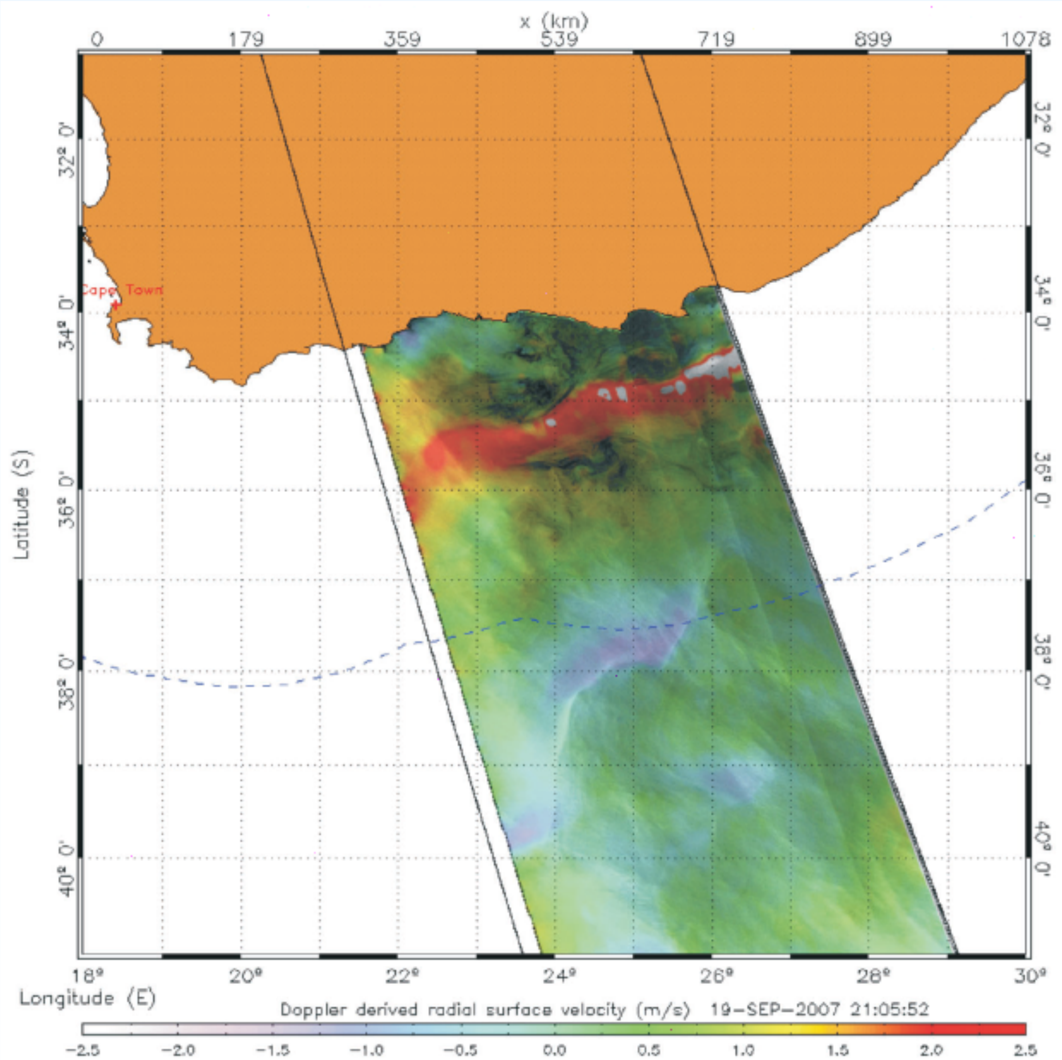
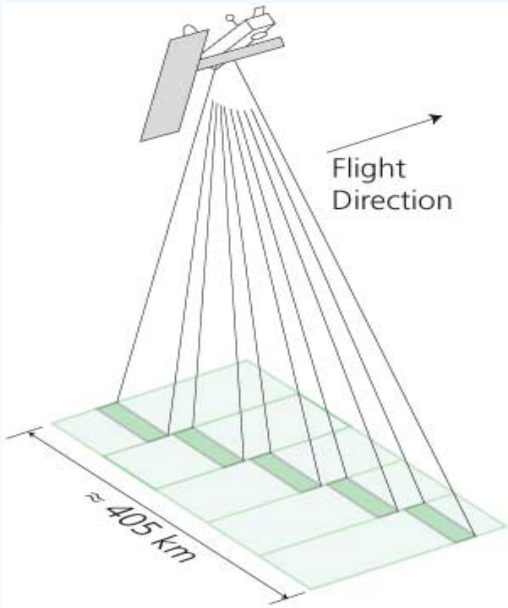


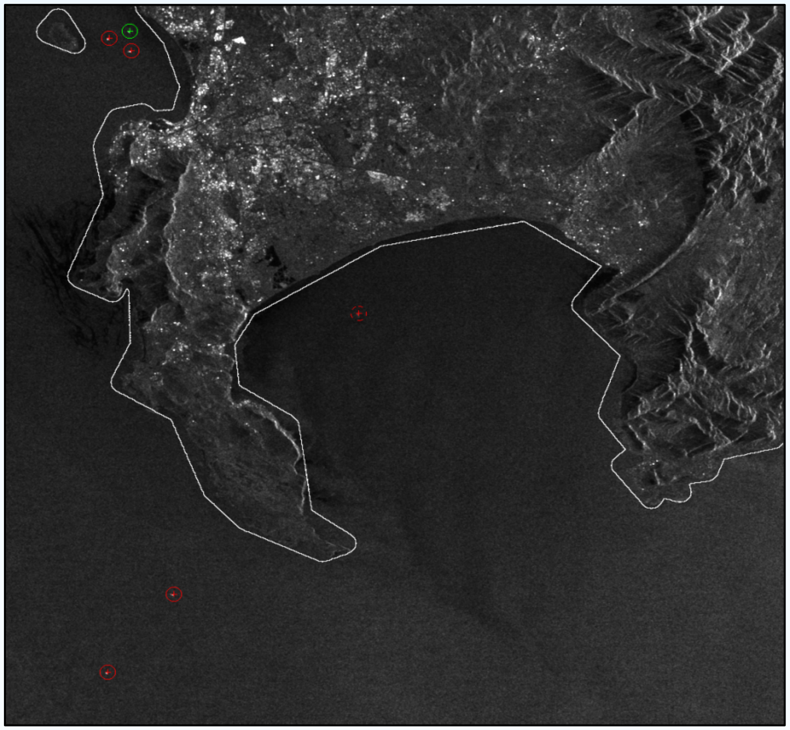
Fig. 1. Surface radial velocity in the Agulhas Current region. Credit: CLS radar division.

ASAR Wide Swath mode uses five predetermined overlapping antenna beams to make up the swath.

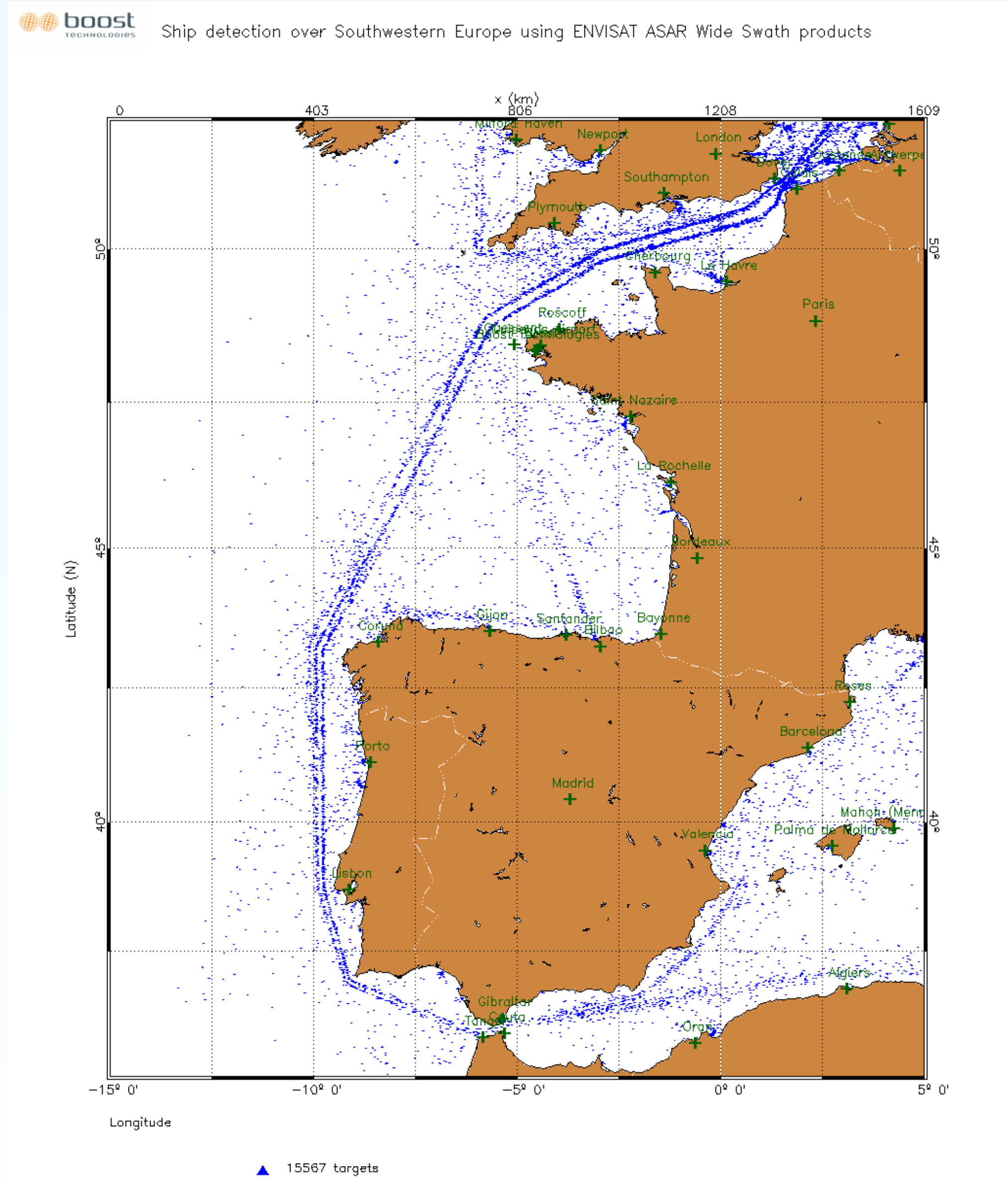


- Coverage = 400 km by 400 km wide swath image
- Spatial resolution = 150m by 150m
- 1 ascending and 1 descending path every 3 days in the Agulhas Current region since July 2007

Synthetic Aperture Radars: *Ship detection*



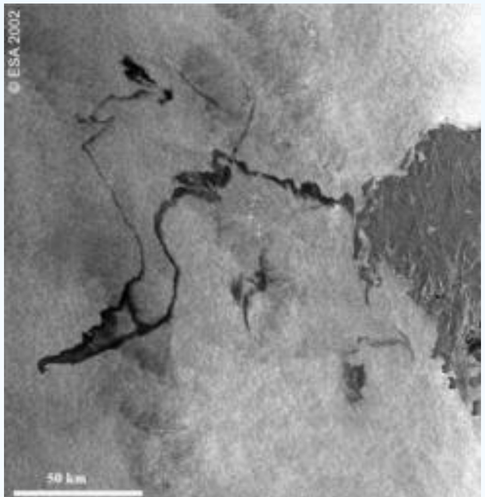
Ships detected around False Bay at a distance greater than 1km from the shore on the 26th August 2007. Green symbols indicate that there is an ambiguity in the detection. Symbols in red indicate a definite ship identifications.



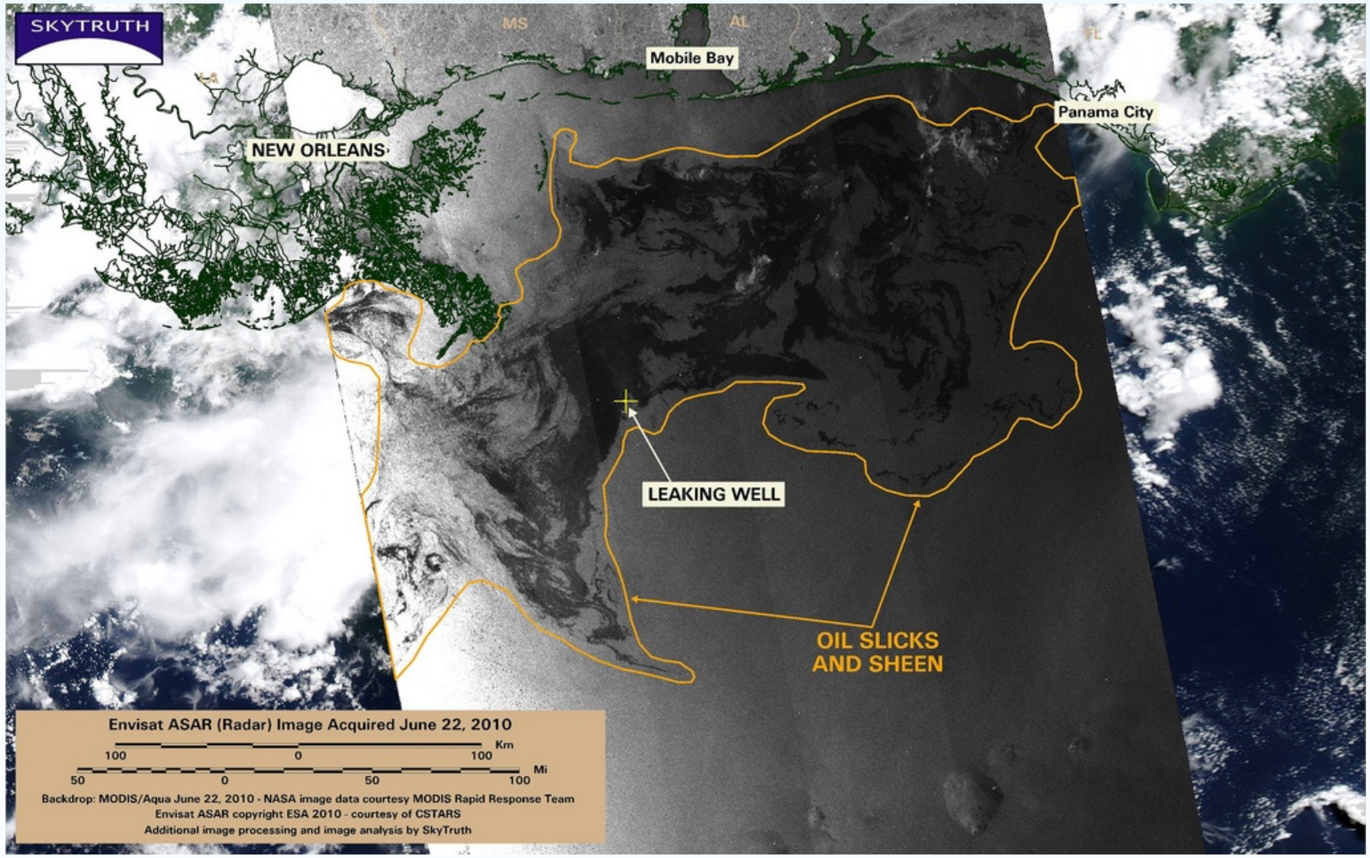
Credit: CLS radar division

Synthetic Aperture Radars: Oils spill detection

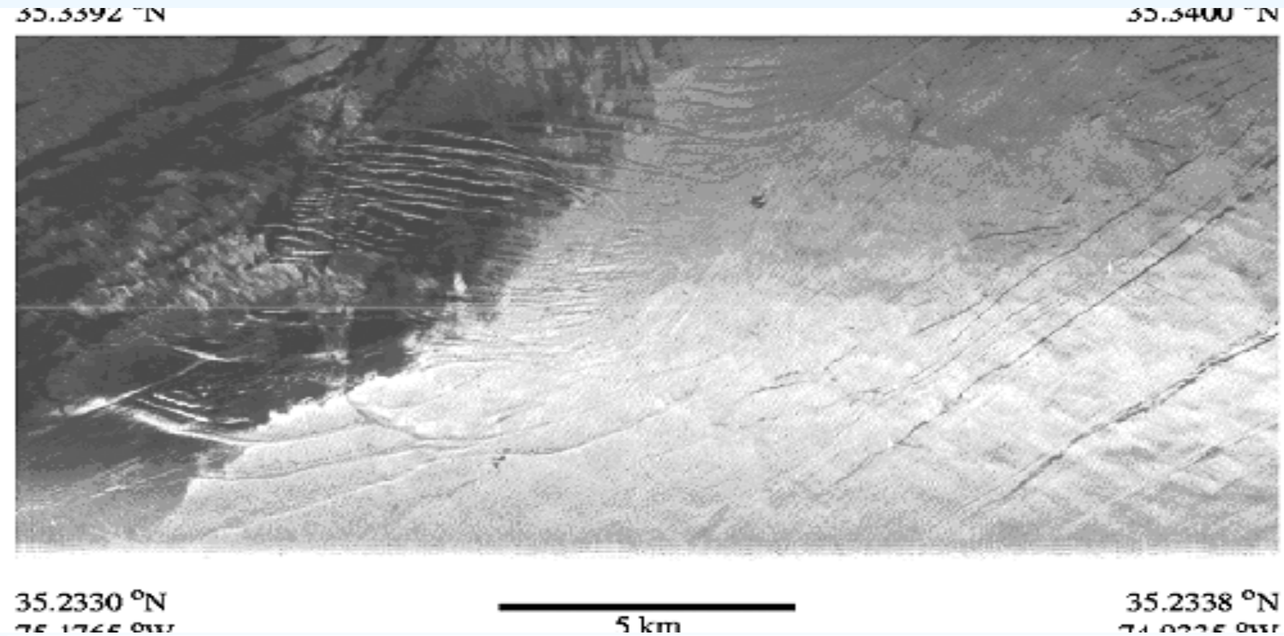
Prestige oil spill
Galicia – November 2002



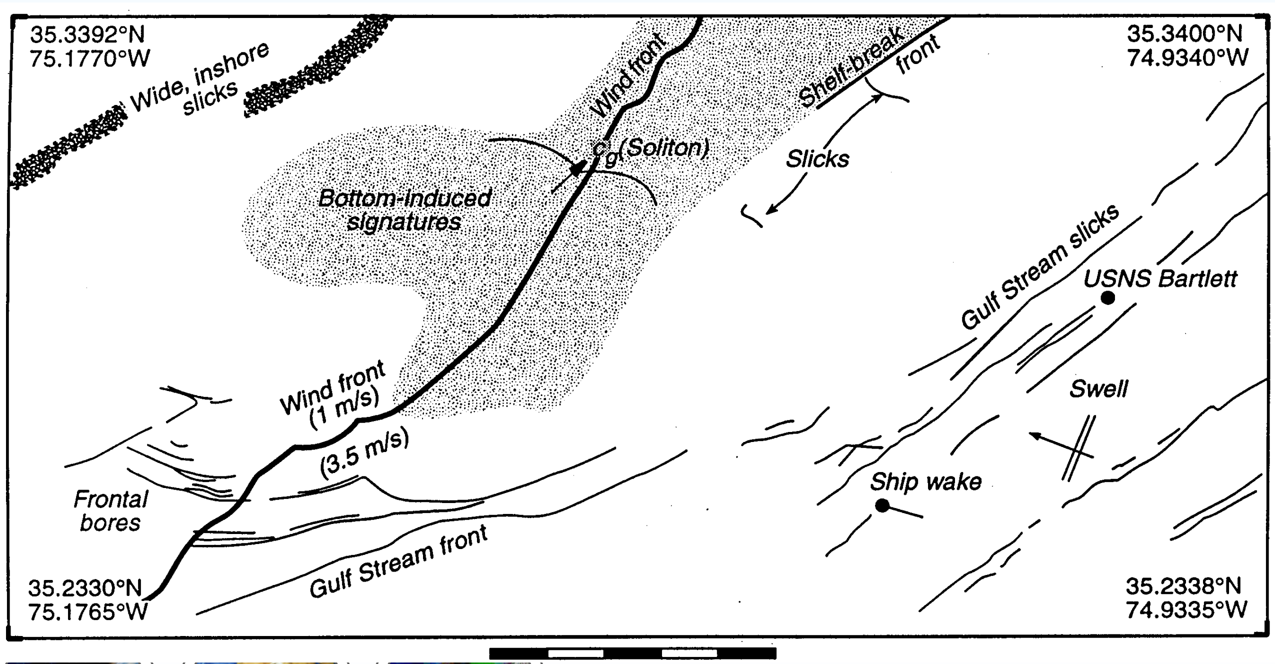
BP oil spill
Gulf of Mexico – June 2010



Synthetic Aperture Radars: Observing the ocean

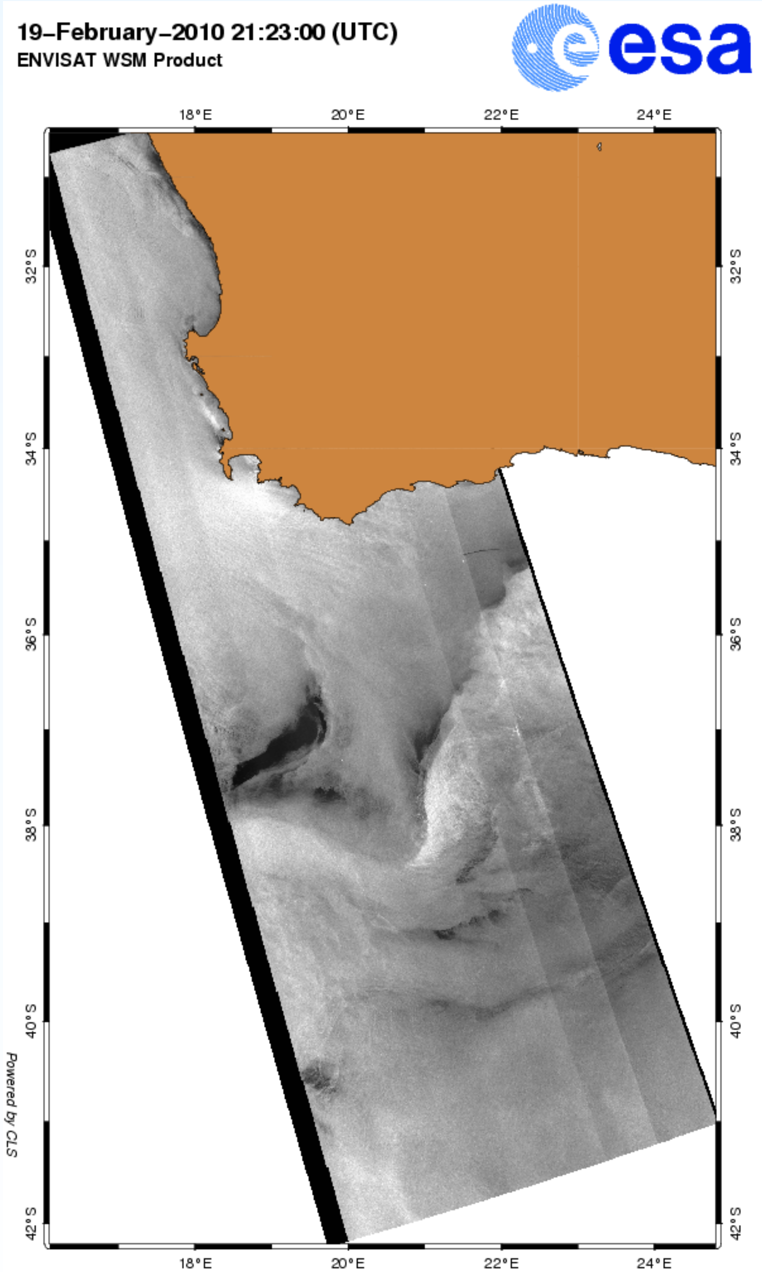


(a) Aircraft L-band VV SAR image that includes the north wall of the Gulf Stream and adjacent shelf near Cape Hatteras,



(b) Sketch map of detectable features and conditions in (a) including the USNS Bartlett. [After Lyzenga and Marmorino, 1998]

Synthetic Aperture Radars: Observing the ocean



Synthetic Aperture Radars: the future

The number of SAR missions is booming

SAR satellite missions	Owner	Launch date (planned)	Frequency band
ERS-2	ESA	March 1995	C
Radarsat-1	CSA (operated by MDA)	November 1995	C
ENVISAT	ESA	March 2002	C
ALOS PALSAR	JAXA	January 2006	L
COSMO SkyMed	ASI	June 2007	X
TerraSAR X	DLR	June 2007	X
Radarsat-2	MDA	December 2007	C
SAOCOM (SIASGE)	CONAE	2008	L
RISAT	ISRO	2008	C
Sentinel1	ESA	2013	C
HayYang-3	SOA	2012	X
Radarsat-C	?	2012	C

Useful URLs

- ESA Earth Remote Sensing Home Page: http://earth.esa.int/
- Canada Centre for Remote Sensing: http://www.ccrs.nrcan.gc.ca/
- The German Remote Sensing Data Center: http://www.dfd.dlr.de/
- The NASA/JPL Imaging Radar Home Page: http://southport.jpl.nasa.gov/
- Remote Sensing Platforms and Sensors: http://quercus.art.man.ac.uk/rs/sat_list.cfm
- UCT Dept. Electr. Eng.: http://www.rrsg.uct.ac.za/applications/applications.html