An introduction to Synthetic Aperture Radar observations

Marjolaine Rouault
Ecosystem Earth Observation – CSIR
mrouault@csir.co.za
**From imaging radars to Synthetic Aperture Radars**

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

A Radar is a Radio Detection And Ranging 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
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.
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

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Years</th>
<th>Agency</th>
<th>Frequency - Polarisation</th>
<th>Resolution - Swath</th>
<th>Special</th>
</tr>
</thead>
<tbody>
<tr>
<td>ERS-1</td>
<td>1991-2000</td>
<td>ESA</td>
<td>C - VV</td>
<td>25 m 100 km</td>
<td>Interferometry (with ERS-2)</td>
</tr>
<tr>
<td>JERS</td>
<td>1992-1998</td>
<td>NASA</td>
<td>L-HH</td>
<td>25 m 100 km</td>
<td>Region. mosaic available</td>
</tr>
<tr>
<td>ERS-2</td>
<td>1995</td>
<td>ESA</td>
<td>C - VV</td>
<td>25 m 100 km</td>
<td>Interferometry (with ERS-1)</td>
</tr>
<tr>
<td>RADARSAT-1</td>
<td>1995</td>
<td>CSA</td>
<td>C - HH</td>
<td>10 - 100 m 45 - 500 km</td>
<td>Multi-incidence</td>
</tr>
<tr>
<td>ENVISAT - ASAR</td>
<td>2002</td>
<td>ESA</td>
<td>C - HH/VV/HV</td>
<td>25 - 1000 m 50 - 500 km</td>
<td>Multi-incidence</td>
</tr>
<tr>
<td>ALOS - PALSAR</td>
<td>2006</td>
<td>JAXA</td>
<td>L - Polarimetric</td>
<td>10 - 100 m 100 - 350 km</td>
<td>Multi-incidence</td>
</tr>
<tr>
<td>TerraSAR-X Cosmo-Skymed</td>
<td>2007</td>
<td>DLR Italy</td>
<td>X-Polarimetric</td>
<td>1 m</td>
<td>Interferometry (1 day)</td>
</tr>
<tr>
<td>RADARSAT 2</td>
<td>2008 ?</td>
<td>CSA</td>
<td>C - Polarimetric</td>
<td>&lt; 10 m</td>
<td>Multi-incidence</td>
</tr>
</tbody>
</table>
ERS-2 and Envisat in tandem flight
Synthetic Aperture Radar: introduction

Radarsat - 2

Sentinel – 1
Planned for launch in 2013
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
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.
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
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 ($= 3 \text{ cm}$).

In the case of L-band ($= 23 \text{ cm}$), 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
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:

\[ \text{Azimuth resolution: } X_a \frac{h}{L \cos} \]
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.
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*

The Azimuthal bandwidth of the SAR is $B = 2f_d$

The **time interval** that can be resolved is

$$\Delta t = \frac{1}{B} = \frac{1}{2f_d} = \frac{\lambda}{2V\theta} = \frac{D}{2V} \text{ (because of } \theta = \frac{\lambda}{D})$$

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

$f_d = \frac{V\theta}{\lambda}$

$f_d = 0$

$f_d = \frac{V\theta}{\lambda}$

$f_d = \text{Doppler shift}$
**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**
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.
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 the same target!

**Range resolution**  
(here \( B = \text{bandwith}, \Theta = \text{radar incidence angle} \))

\[
X_r = \frac{c \tau}{2 \sin \Theta} = \frac{c}{2B \sin \Theta}
\]

Good range resolution for:  
- short pulse  
- Large incidence angle
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 **artificially induced by the emitted signal**.

All civilian spaceborne SARs, and most civilian airborne SARs use linear FM chirps as the modulation scheme.
These effects enhance the visual appearance of relief and terrain structure, making radar imagery excellent for applications such as topographic mapping and identifying geologic structure.
SAR processing can be considered as a two-dimensional focusing operation:

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

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.
Synthetic Aperture Radars: Data processing

Speckle in SAR

SAR image

optical image
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.
At the ocean's surface radar echoes from SARs are reflected through **Bragg Scattering**

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).

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

\[ \lambda_s = \frac{\lambda_r}{2 \sin \theta} \]

where:
- $\lambda_r$ radar wavelength
- $\lambda_s$ sea surface wavelength
- $\theta$ incidence angle
Synthetic Aperture Radars: Observing the ocean

Bragg scattering is affected by wind

Radar backscatter increases with wind speed

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
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
Long waves change the slope of the small Bragg waves, with maximum backscatter on the face of the wave, $90^\circ$ out of phase with the wave amplitude.
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]
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

Radar backscatter increases with wind speed
Backscatter $\sigma$ depends on:

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

One measurement of $\sigma$ 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 $\sigma$ to wind speeds. These functions are tuned to co-located:

- ECMWF 10 m winds
- ERS-1 scatterometer data ($\sigma$)

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 image located near the DW1 instrument (Fig. 3). 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.

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
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.
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

- 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

ASAR Wide Swath mode uses five predetermined overlapping antenna beams to make up the swath.
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.
Synthetic Aperture Radars: Oils spill detection

Prestige oil spill
Galicia – November 2002

BP oil spill
Gulf of Mexico – June 2010
(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
The number of SAR missions is booming

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

- The German Remote Sensing Data Center: [http://wwwdfd.dlr.de/](http://wwwdfd.dlr.de/)
- Remote Sensing Platforms and Sensors: [http://quercus.art.man.ac.uk/rs/sat_list.cfm](http://quercus.art.man.ac.uk/rs/sat_list.cfm)