HAZARD: FLOOD

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Introduction

It is well known that flood affects societies, economies, and ecosystems worldwide at certain times and places, having devastating impacts.

By 2050, worldwide annual losses due to flooding are predicted to reach $1 trillion for coastal cities.

Useful information about flood extent and inundated area can be obtained from remote sensing platforms, either airborne or space-borne.

Surface water area and associated changes can be used in a variety of applications, ranging from simple mapping and monitoring of water bodies to more complex water quality assessments of lakes and reservoirs.

Introduction

Inundation area extent is commonly used to assess the magnitude of a flood event with the aim to support relief services and to calibrate and validate flood inundation (i.e. hydraulic) models.

While the mapping of permanent water bodies may be done with most satellite imaging platforms at almost any time, obtaining the area and extent of a flood is rather opportunistic. Indeed, certain conditions on both the Earth surface and atmosphere during an event (such as emergent flooded vegetation and persistent cloud cover) may restrict suitable data acquisition technology only to a few remote sensing instruments, such as microwave sensors.

Given the rapid flood recession in small to medium sized catchments and weather conditions during events, flood detection is realistically feasible only with synthetic aperture radar (SAR) imagery.

Introduction

Flood is not only one of the most widespread natural disasters, which regularly causes large numbers of casualties with rising economic loss, extensive homelessness, and disaster induced disease, but it is also the most frequent natural disaster.

According to statistics of the International Charter “Space and Major Disaster,” 60% of the total number of activations are related to floods.

A raising awareness of satellite-based crisis information has led to an increase in requests to corresponding value adders to support civil-protection and relief organizations with disaster-related mapping and analysis.

Introduction

Environmental and humanitarian agencies around the world support communities in protecting lives and property by providing tools and information to help them understand local flood risk and make cost-effective mitigation decisions

The scientific literature of mapping surface water (i.e. detection of permanent water bodies and flooding) from SAR imagery is rapidly growing, and significantly so over the past decades.

This increases on number of publications coincides with recent launches of Earth-orbiting satellites carrying very high-resolution SAR instruments (e.g. TerraSAR-X, COSMO-SkyMed, Radarsat-2, Sentinel-1, SAOCOM, ALOS-PALSAR).

Introduction

With the availability of more and more satellite data, the extraction of floodwater extent using remote sensing data is gaining an important role in all the phases of hazard management, from the alert and preparedness phase to the emergency management and up to the post-event damage assessment.

Monitoring floodwater is also in the 2030 Agenda for Sustainable Development, which aims to assist countries to measure, manage and monitor progress on economic, social and environmental sustainability, where one of the target is to restore degraded land and soil, including those affected by desertification, drought and floods.

Introduction

The Copernicus program, a joint effort between the European Space Agency (ESA) and the European commission (EC), is having a disruptive effect in the flood hazard and, more broadly, the emergency management field, thanks to its capability to acquire EO-data systematically, globally and frequently.

For disaster responders, having access to a massive amount of satellite data does not have any intrinsic operational value. The large amount of data only becomes relevant if they are rapidly translated into maps that can be used to manage the emergency operations.

Scattering mechanisms

The backscattering is composed of:

- surface scattering
- volume scattering
- strong scattering (surface-surface)

Their relative contribution is governed by:

- surface roughness
- dielectric properties of the medium

All of them depend on:

- the radar frequency
- the polarisation
- the incidence angle

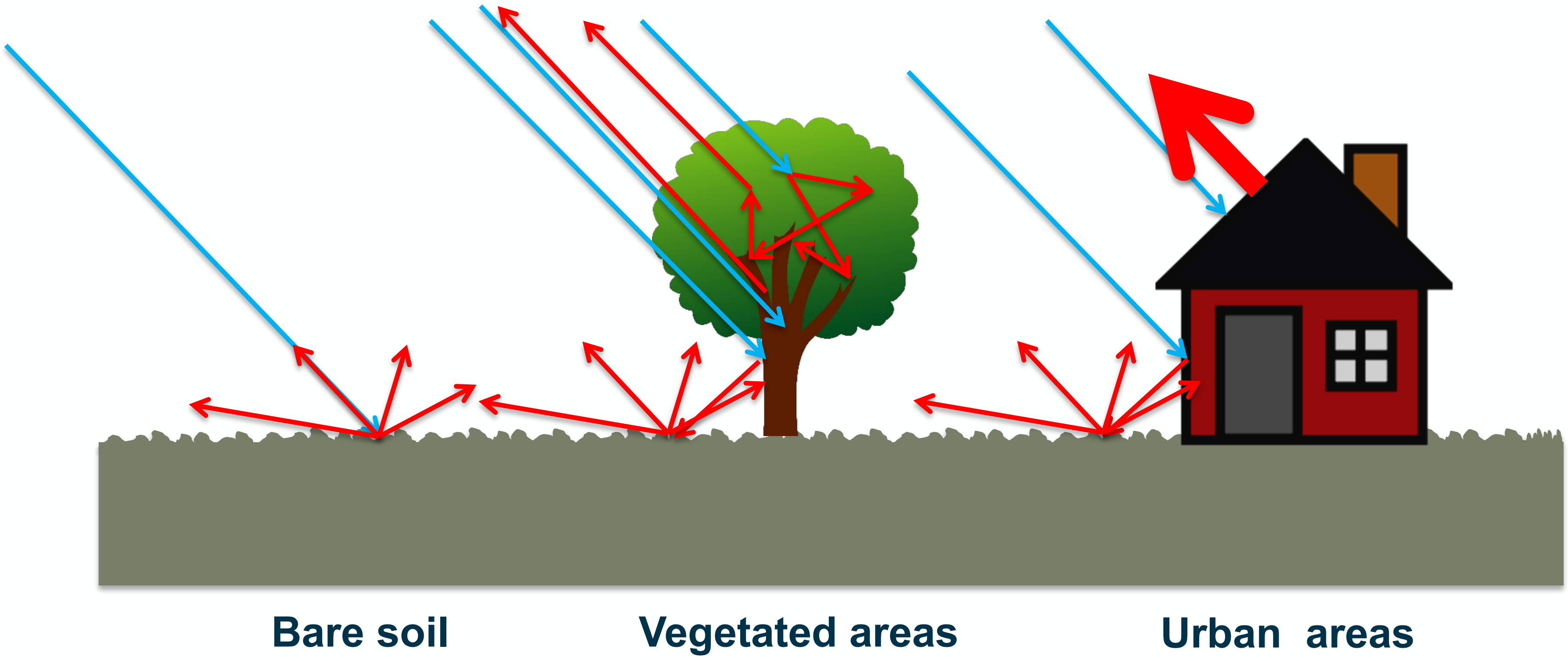
Scattering mechanisms

Surface scattering in which the energy can be seen to scatter or reflect from a well-defined interface.

Volume scattering, for which there is no identifiable single or countable number of scattering sites; instead, the reflections are seen to come from a myriad of scattering elements, such as the components of a tree canopy.

Strong scattering can come in a variety of forms. Two types are corner and dihedral reflector behaviour, both of which give particularly strong responses in radar imagery.

Scattering over different land covers



Surface scattering

The strength of surface scattering depends on the roughness of the surface and the dielectric constant of the material from which scattering occurs.

To better distinguish its behaviour with respect to the volume scattering one, we say that scattering from a surface occurs when there is an identifiable discontinuity in dielectric constant (such as from air to water, air to soil, and so on).

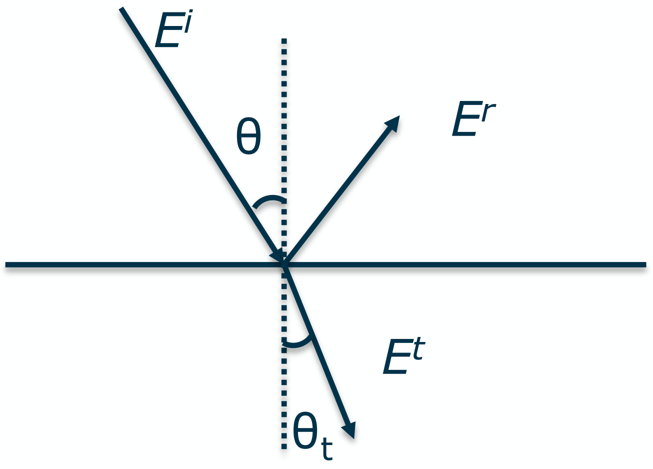
In the case of volume scattering such a single abrupt change in dielectric constant cannot be distinguished. Indeed the individual scattering events within the volume occur at many dielectric discontinuities (air-leaves, air-twigs, and so on).

Moreover, if a surface is very dry the incident energy can penetrate, refract and scatter from sub-surface features.

Surface scattering

To obtain the range resolution, the incidence angle of a SAR sensor is not vertical.

The reflection coefficient depends on the polarisation.



$$\rho_H = \frac{\cos\vartheta - \sqrt{\varepsilon_r - \sin^2\vartheta}}{\cos\vartheta + \sqrt{\varepsilon_r - \sin^2\vartheta}}$$

$$\rho_V = \frac{-\varepsilon_r \cos\vartheta - \sqrt{\varepsilon_r - \sin^2\vartheta}}{\varepsilon_r \cos\vartheta + \sqrt{\varepsilon_r - \sin^2\vartheta}}$$

A smooth surface is specular because it acts like a mirror.

When? $h < \frac{\lambda}{8\cos\vartheta}$ *Rayleigh criterion*

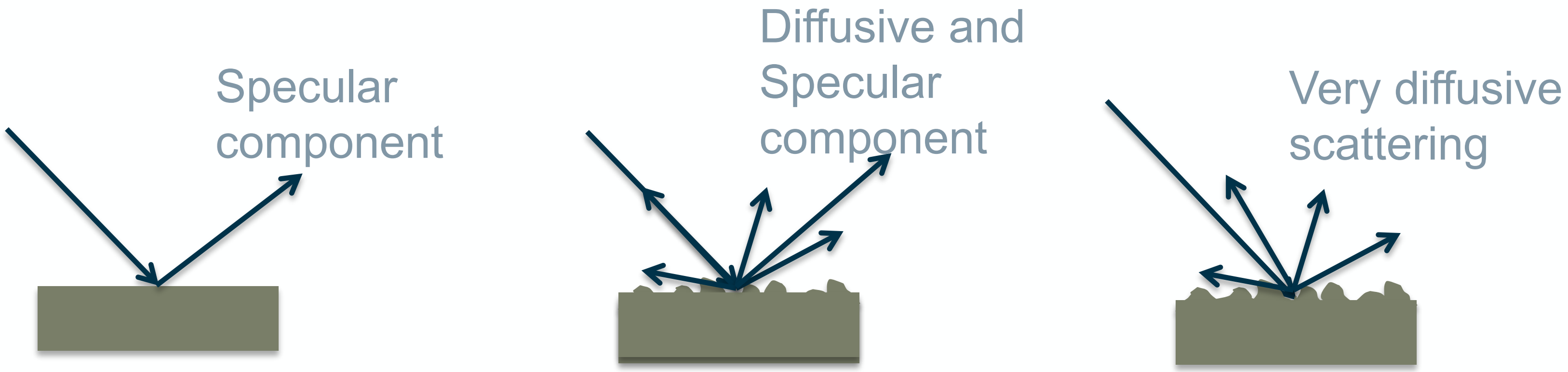
h: standard deviation of surface roughness

Surface scattering

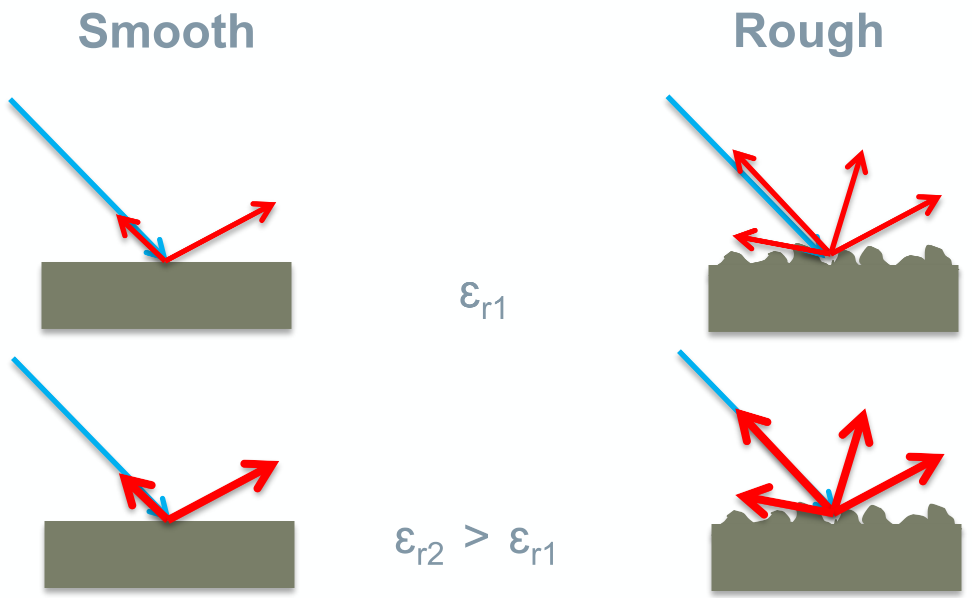
It is to be expected that as the roughness of a surface increases there will be more scattering back to the radar, and that the rougher the surface the lighter it will appear in radar imagery.

If the surface is slightly rough there will be still a specular component, with only a small component of backscatter.

For a very rough surface significant scattering will occur in all directions, including back to the sensor.



Surface scattering



- No depolarization, no cross-pol backscattering
- Fresnel Reflectivity $R_H > R_V$

- Small depolarization, cross-pol backscattering
- Fresnel Reflectivity $R_H = R_V$

Volume scattering

Media such as tree canopies contain many individual scattering sites that collectively contribute to backscattered energy.

Discontinuities in dielectric constant give rise to the scattering. There are many and they are difficult to identify and describe, that understanding how they contribute individually to backscatter is not straightforward.

If we assume a volume scattering by the random set of individual scatterers and if the density of scatterers is uniform it is evident that the volume would look much the same when viewed from any angle, in which case we could conclude that the amount of backscatter will be almost independent of incidence angle.

Volume scattering

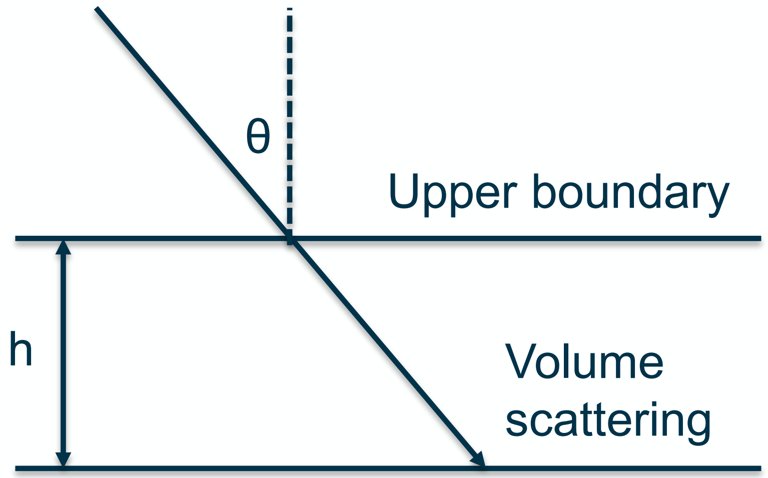
The energy travels into the volume:

it encounters loss in the forward direction as a result of scattering from dielectric inhomogeneities;

the scatterers themselves may also absorb some of the radiation.

In case the volume is very lossy, all forward travelling energy diminishes to zero.

In other case we need to take into account its vertical dimension.



Volume scattering

If scatterers have been assumed to be small and isotropic in their behaviour, we would also expect that the HH and VV responses for random volumes would be comparable.

If the volumes contained scatterers that are not spatially symmetric there is a polarisation dependence.

If a volume is composed of a large collection of thin cylinder-like elements, it exhibits strong cross-polarised behaviour, a situation that is indicative of branches and twigs in a canopy.

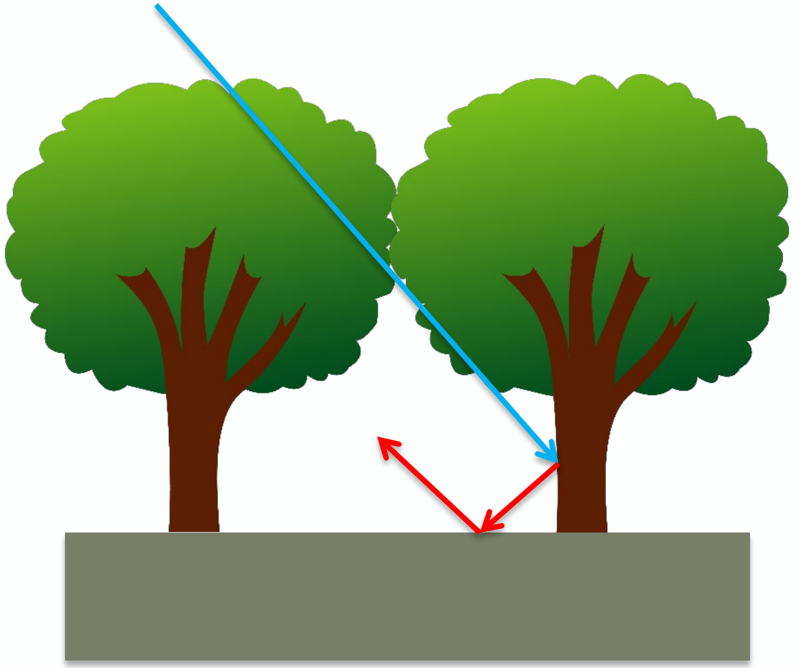
It is characteristic of volume scattering that cross-polarised returns are generally present and comparable in strength to co-polarised scattering, unless the wavelengths are so long that the scattering geometries have little influence.

Vegetated areas

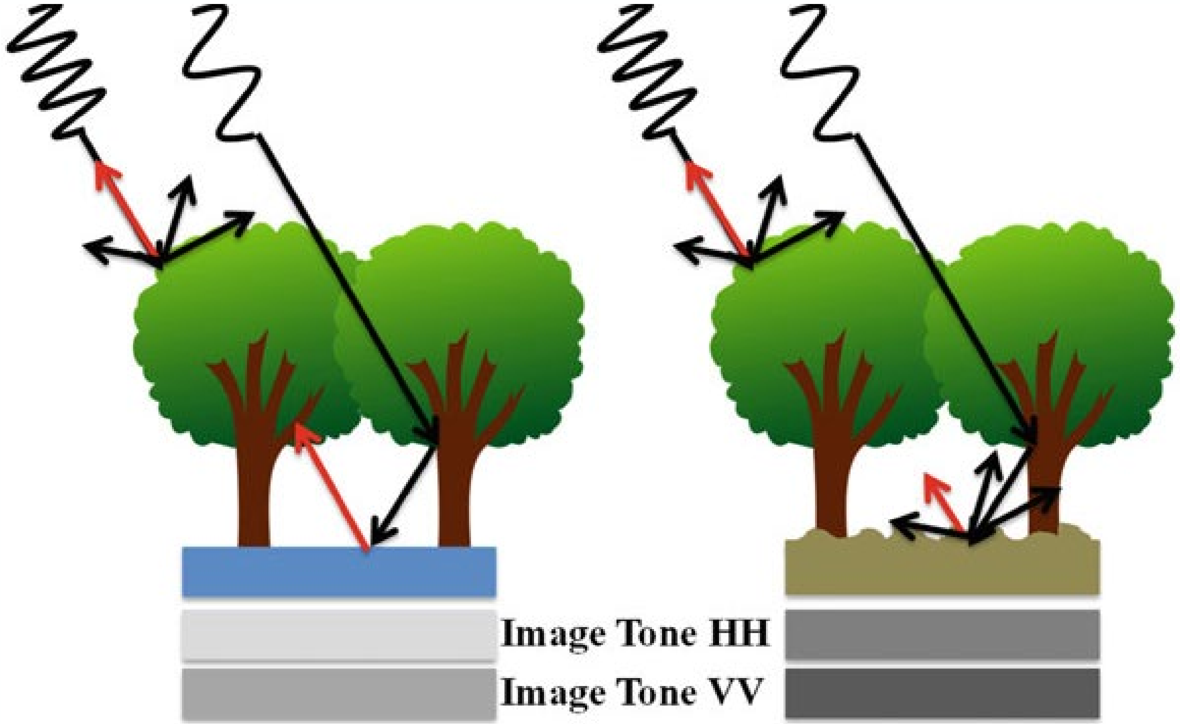
The contrast between flooded and non-flooded vegetation is dependent on the characteristics of the vegetation and the observing system.

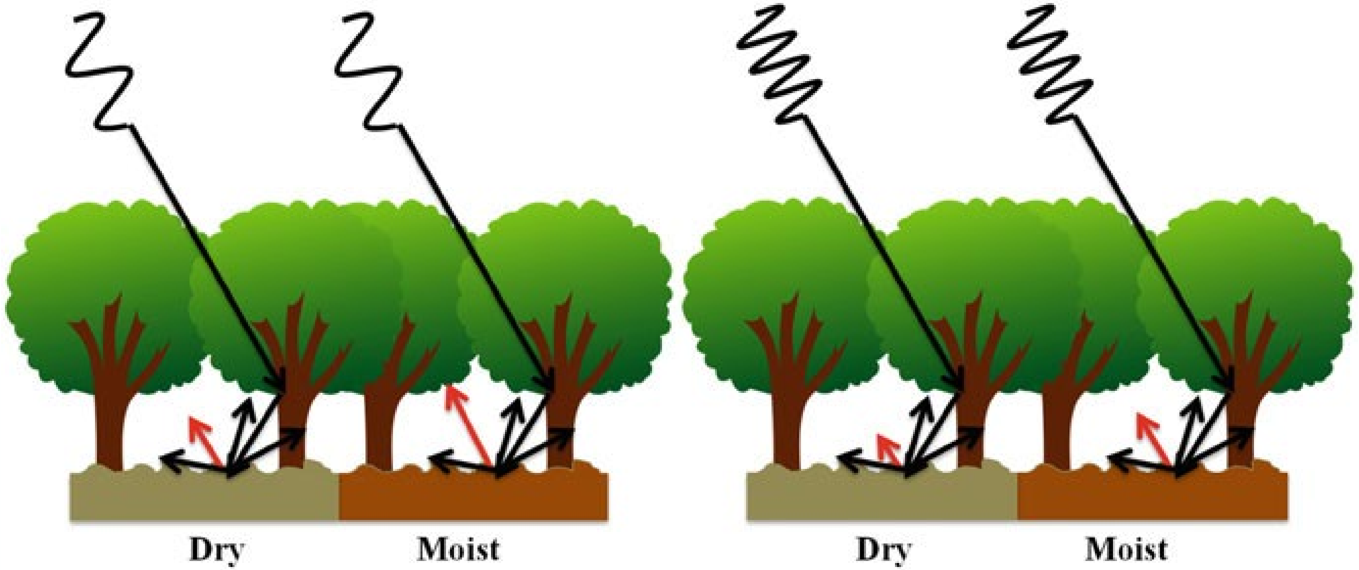
The double-bounce enhancement can become predominant when the radar signal is able to penetrate into the vegetation, as in the case of low vegetation biomass, low frequency, small incidence angle, or proper polarization.

For the predominance of the double-bounce effect, HH observations are preferable, since the specular reflection from the horizontal surface is much higher for horizontally polarized waves compared to vertical waves (where there is a minimum of reflectivity at the Brewster angle of incidence).

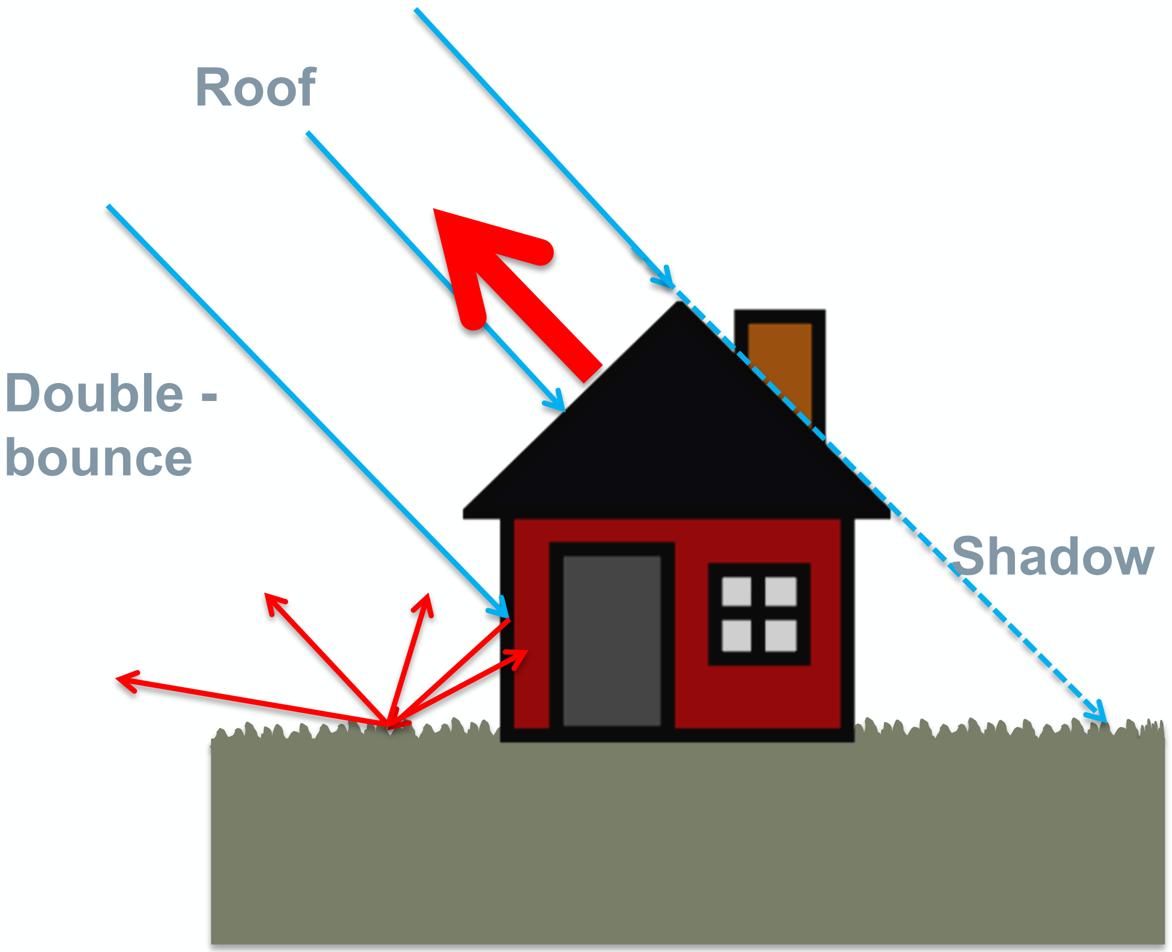


Vegetated areas

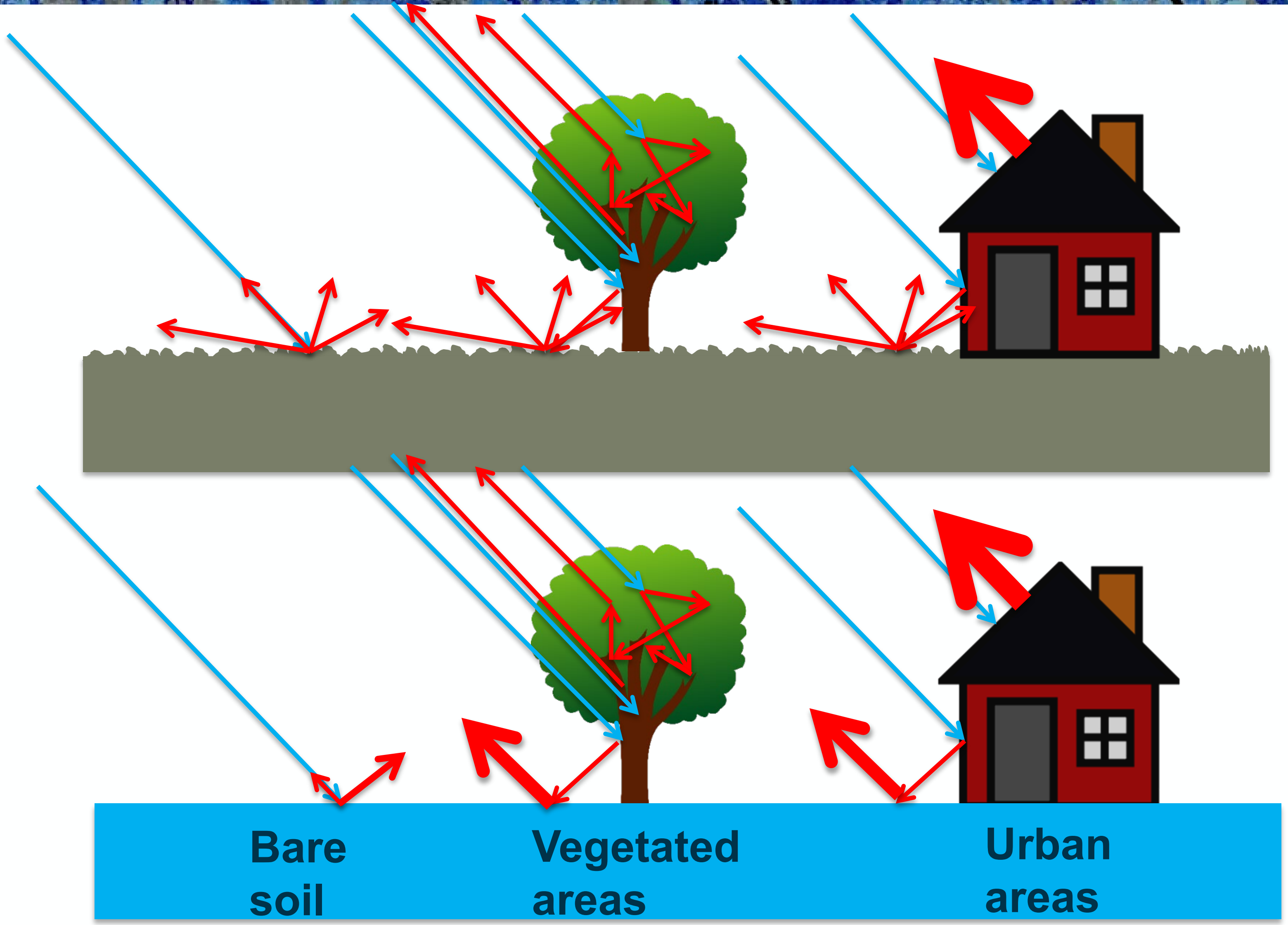




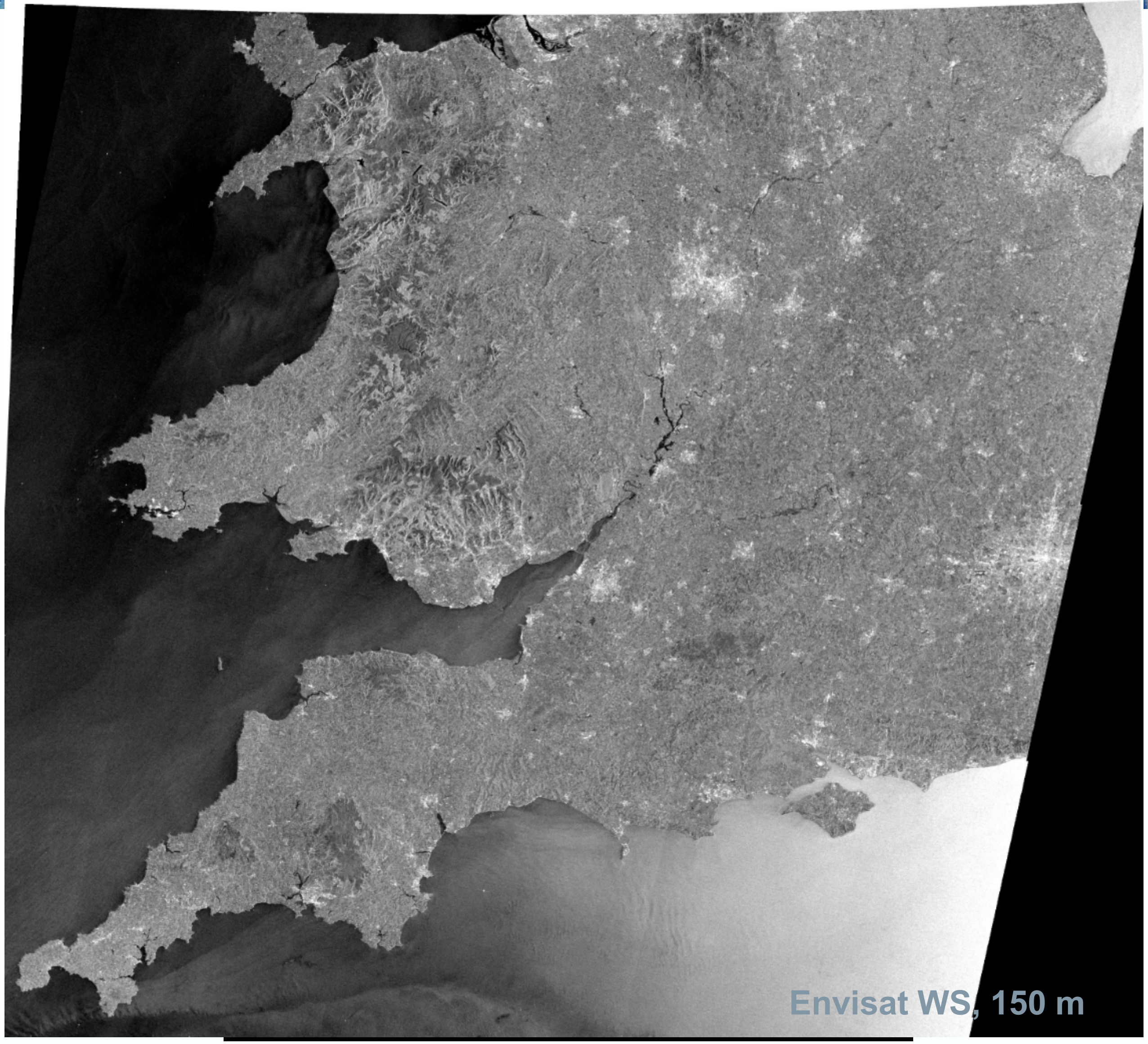
Urban areas



The role of floodwater

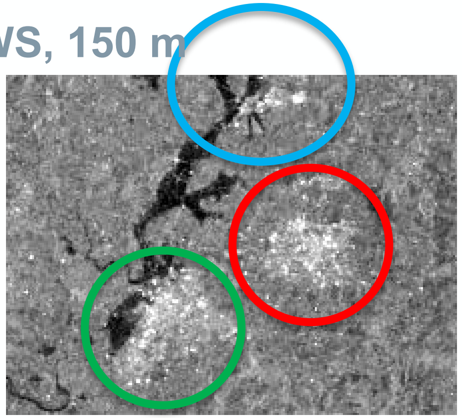


How does a SAR image look like?

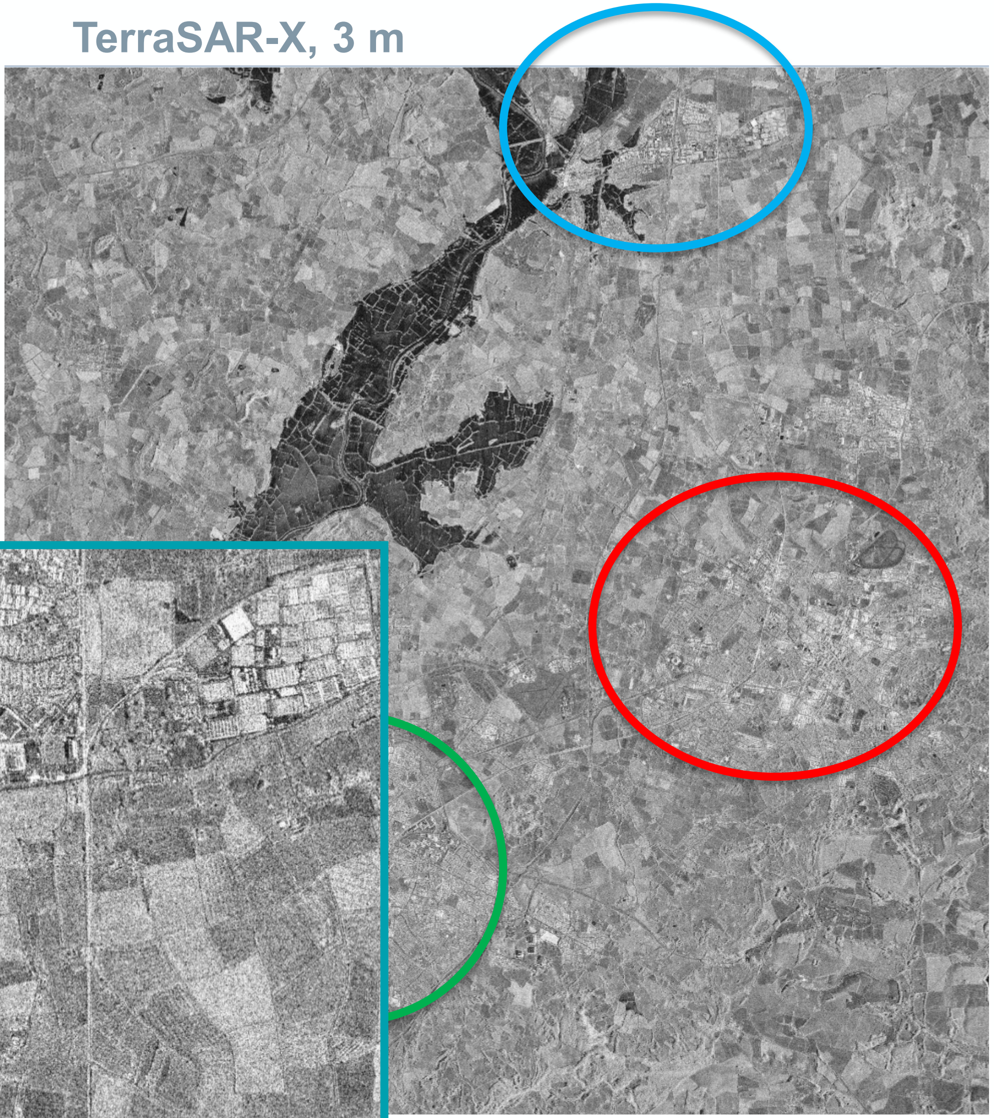


How does a SAR image look like?

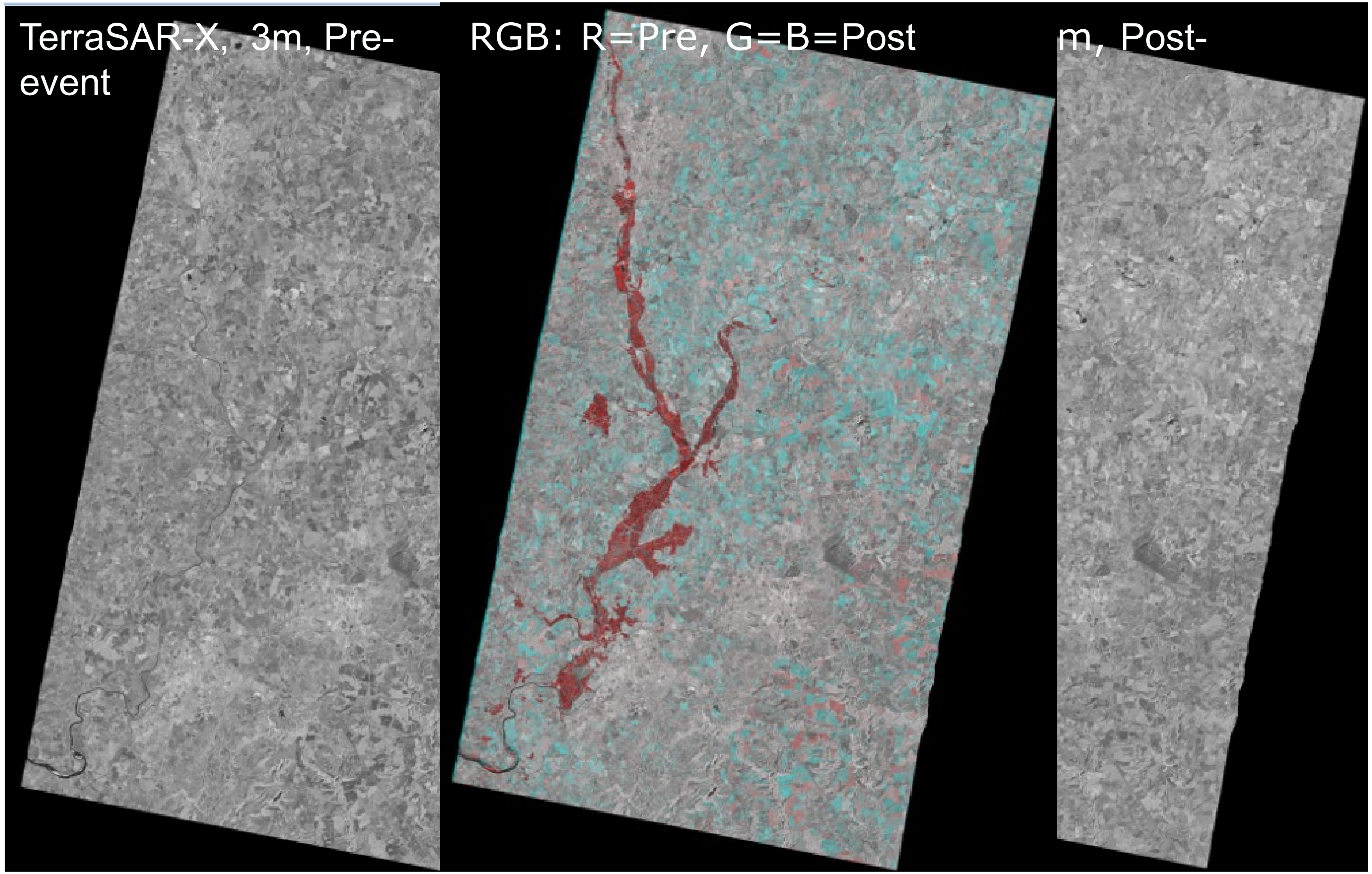
Envisat WS, 150 m



TerraSAR-X, 3 m



How does a SAR image look like?



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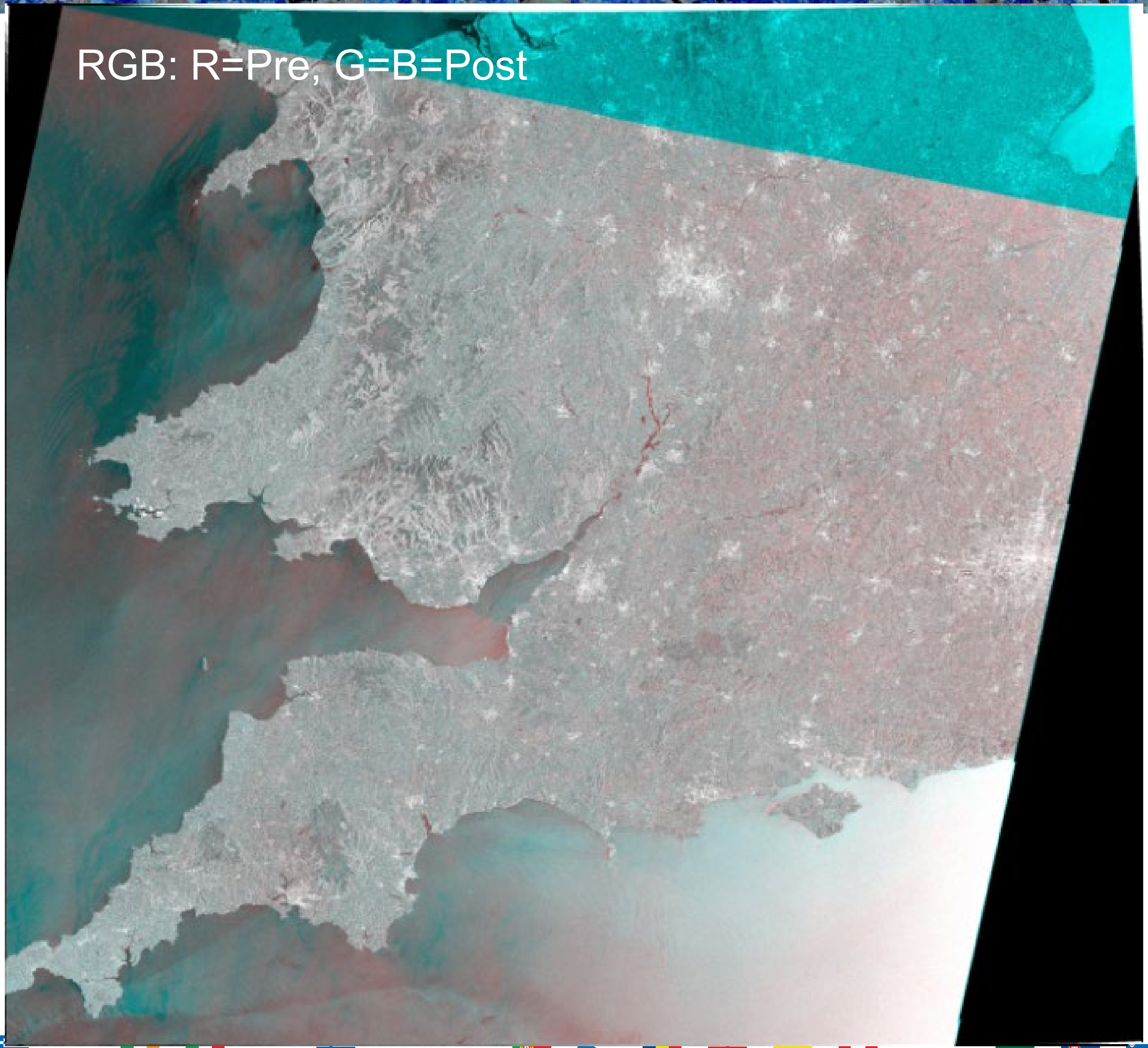
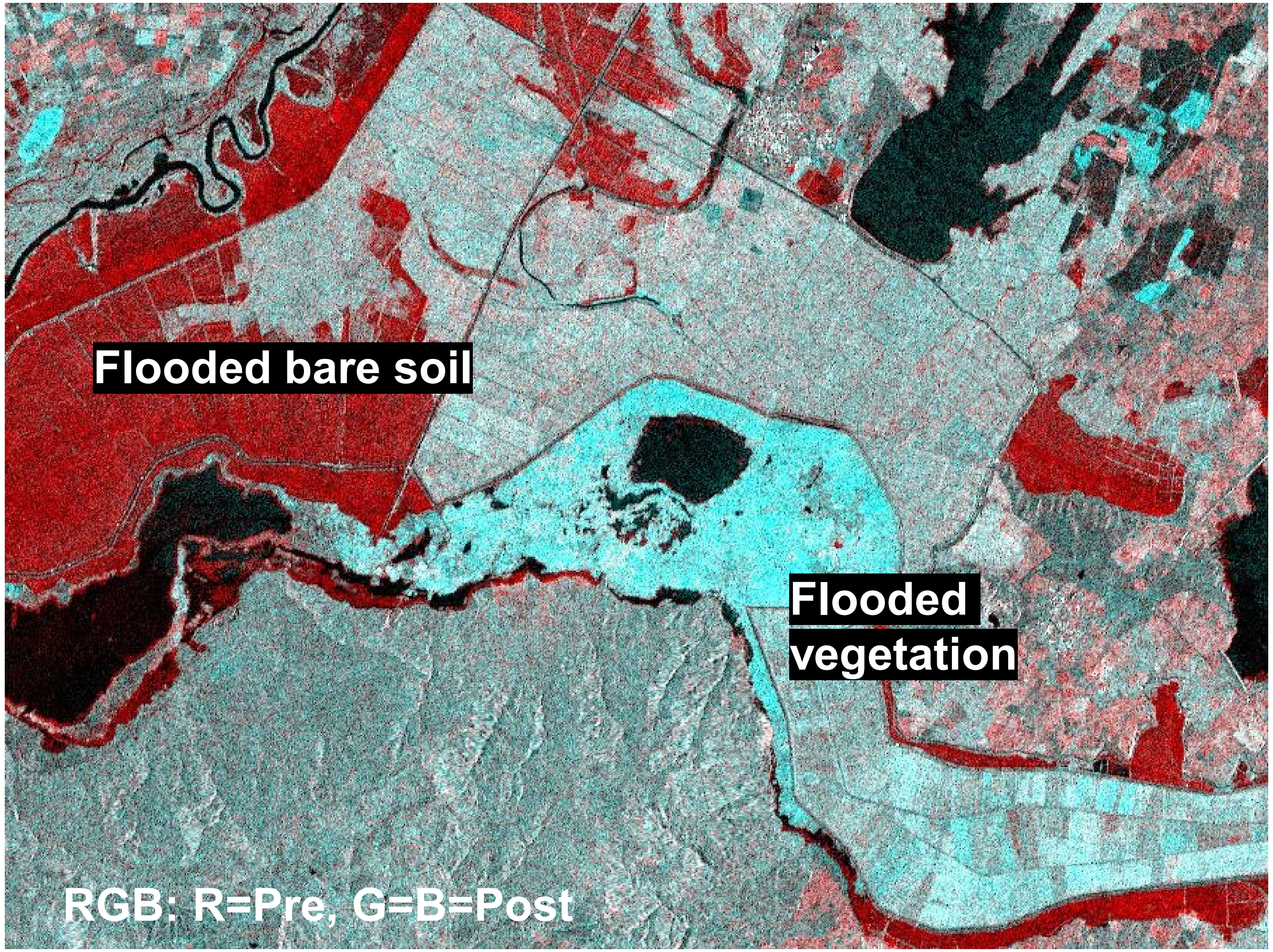
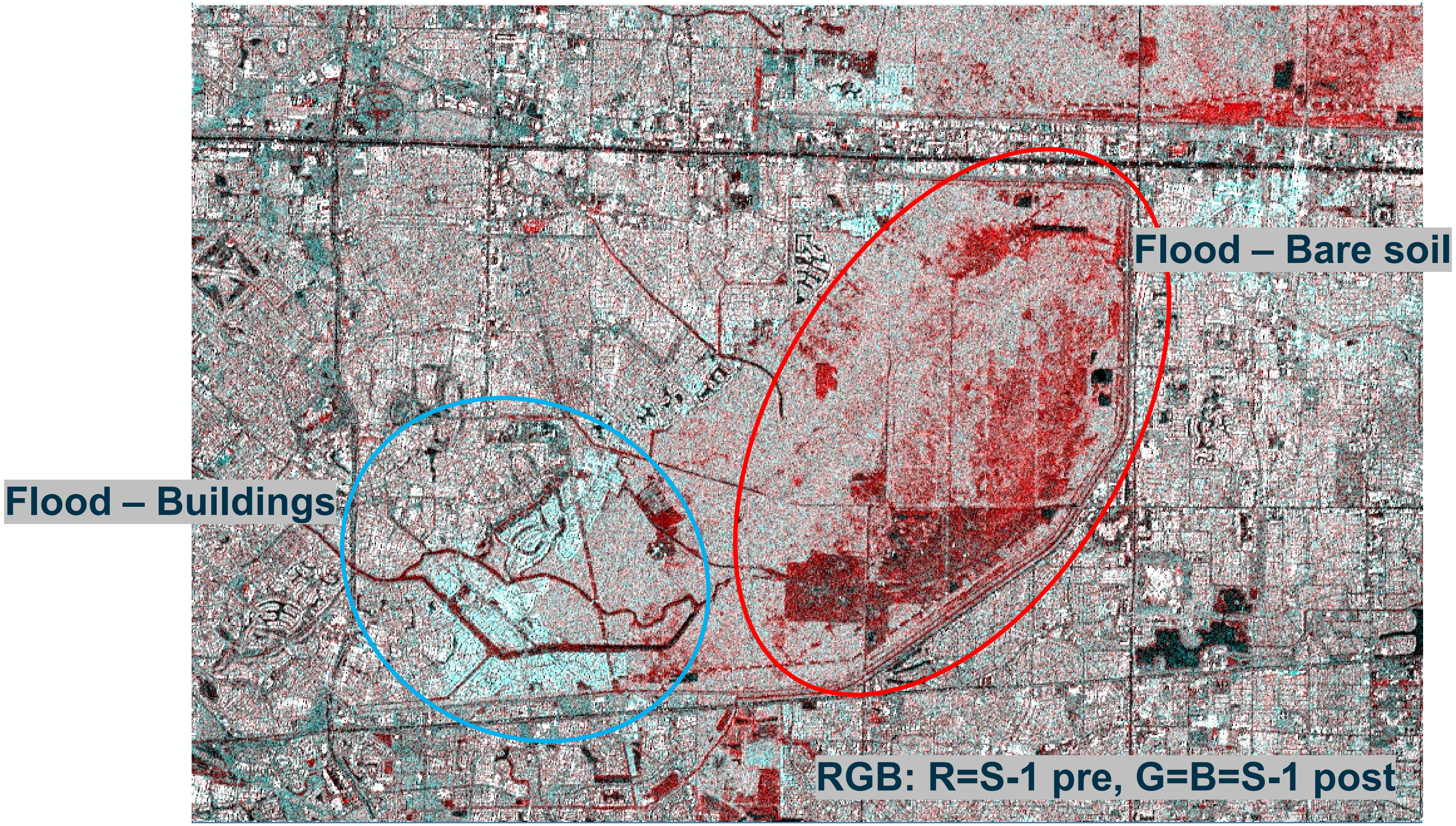


How does a SAR image look like?



How does a SAR image look like?

Sentinel-1



Speckle

The coherent nature of radar illumination causes the speckle effect.

From a statistical point of view, the complex amplitude of the pixel is modeled as the sum of a ‘large number’ of complex elementary contributions.

If the contributions interfere constructively the pixel has a high radiometry.

This mechanism is not random, but it is unpredictable and it is assumed to be a multiplicative noise.

The speckle can be considered fully developed when the responses of each scatterer are independent of the others and the amplitude and the phase are independent.

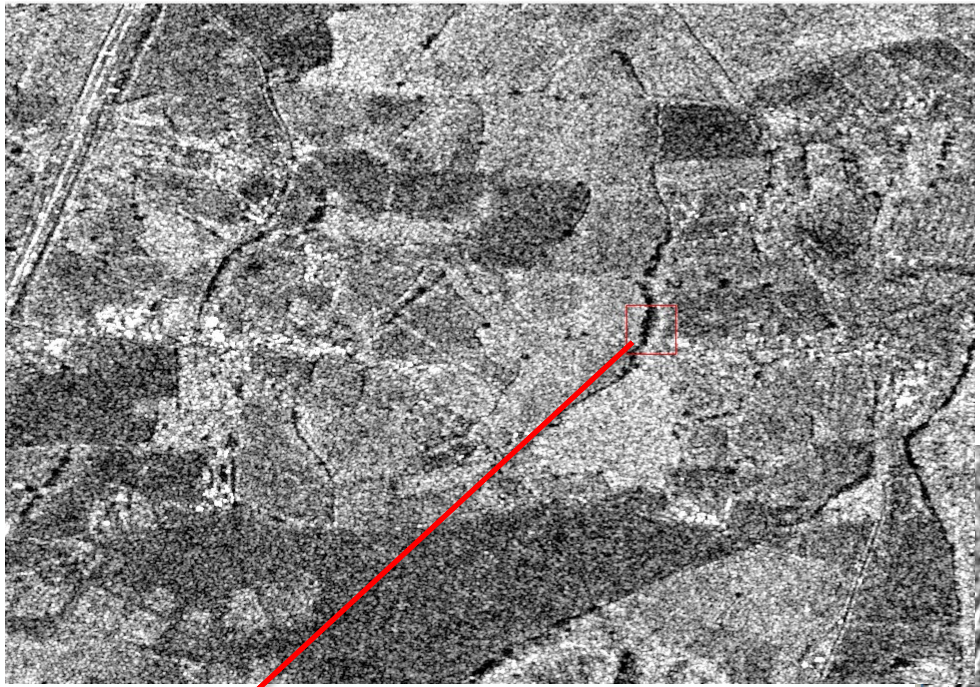
To reduce the speckle - Multilooking

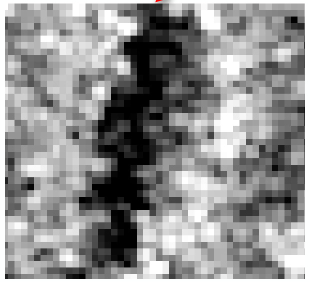
Original SAR image

Multilook 2x2

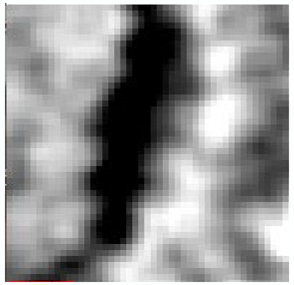
Multilook 4x4

To reduce the speckle - Filtering

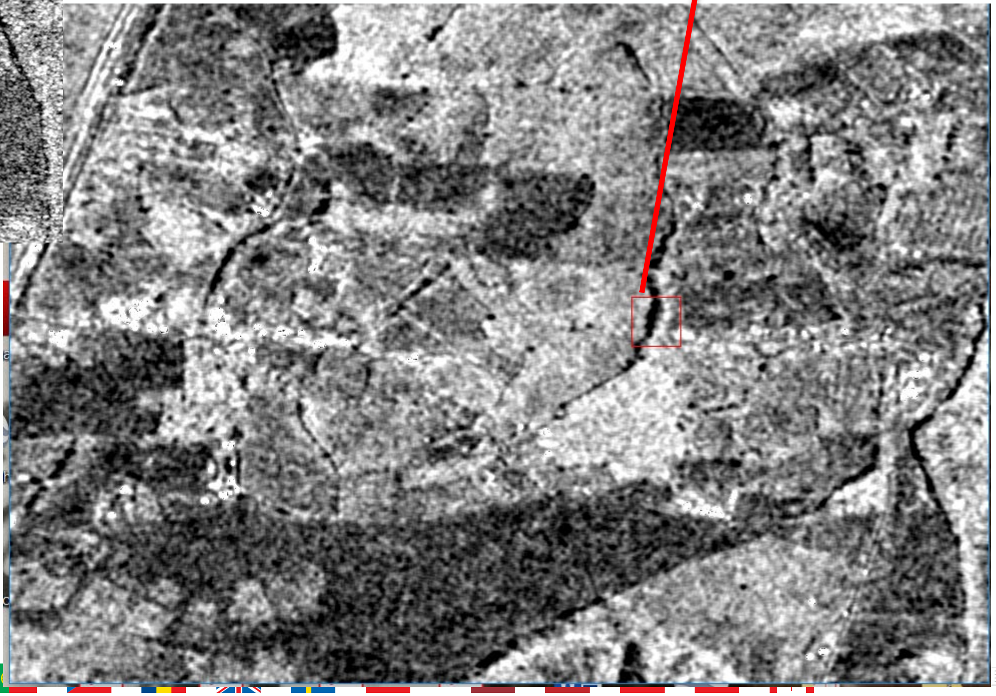




Original SAR image

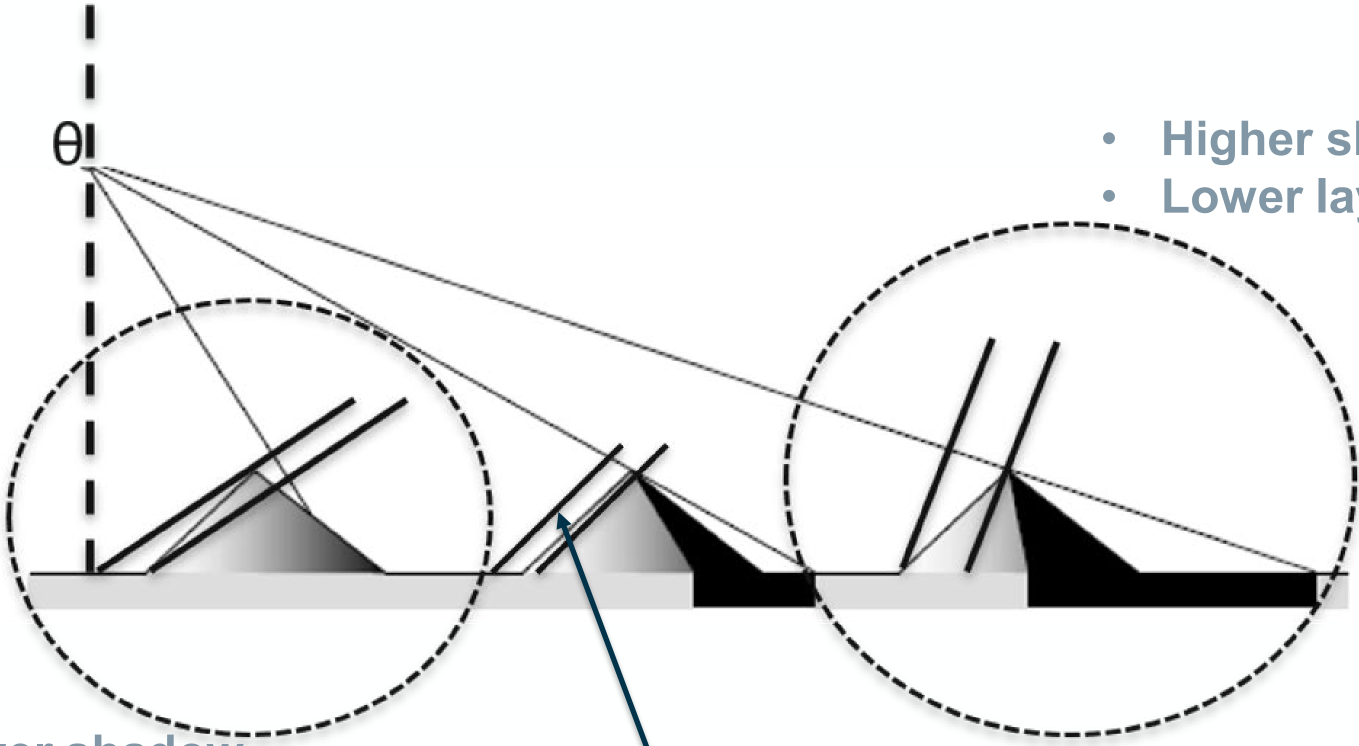


Filtered



Layover, foreshortening and shadow

Geometric effects

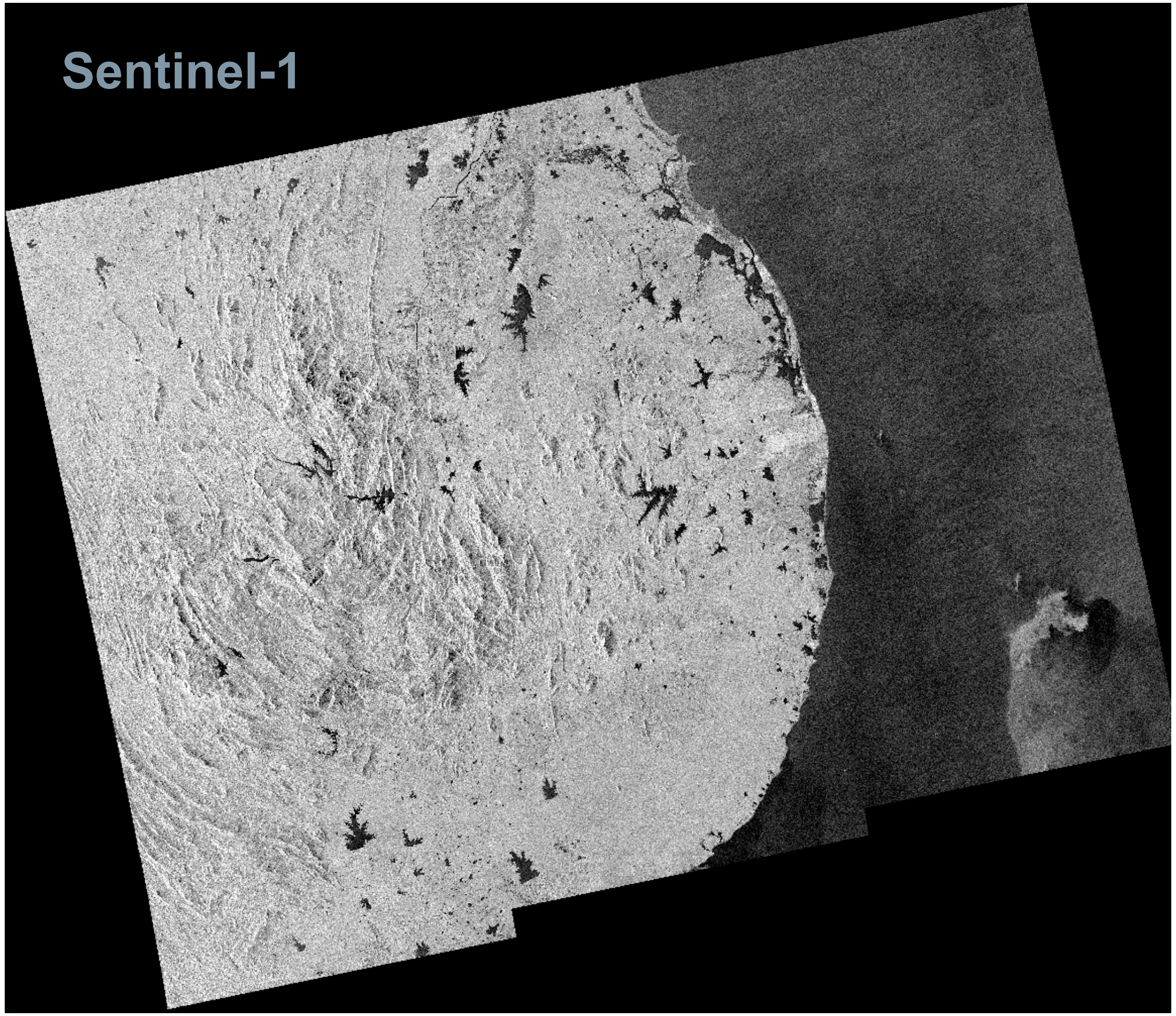


- Higher shadow
- Lower layover

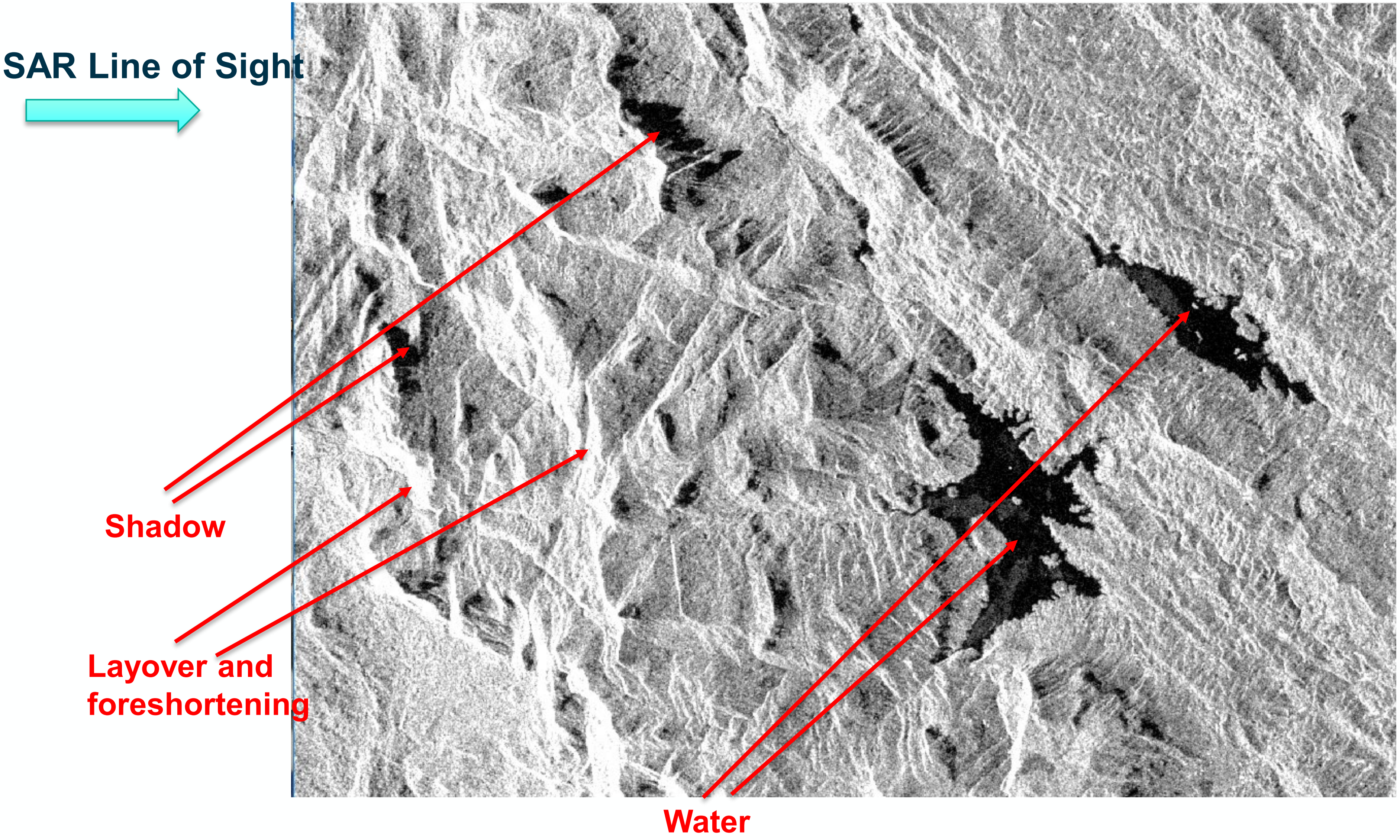
- Lower shadow
- Higher layover

- Foreshortening

Layover, foreshortening and shadow



Layover, foreshortening and shadow



Snow

Considering that most of the automatic flood detection algorithms search for areas of low backscatter appearing dark in SAR images, the possible presence in the image of dark patches caused by surface absorption on wet snow may cause a large overestimation of the floodwater extent.

Indeed, during the snow accumulation period, the dry snowpack is almost transparent to microwaves. As a result, the SAR signal penetrates the snowpack for several meters and the main contribution to the backscattering is from the snow–ground interface.

During the melting period, on the other hand, the increase in the amount of free liquid water inside the snowpack causes high dielectric losses, thereby increasing the absorption coefficient. The corresponding areas appear relatively dark in SAR images.

Snow

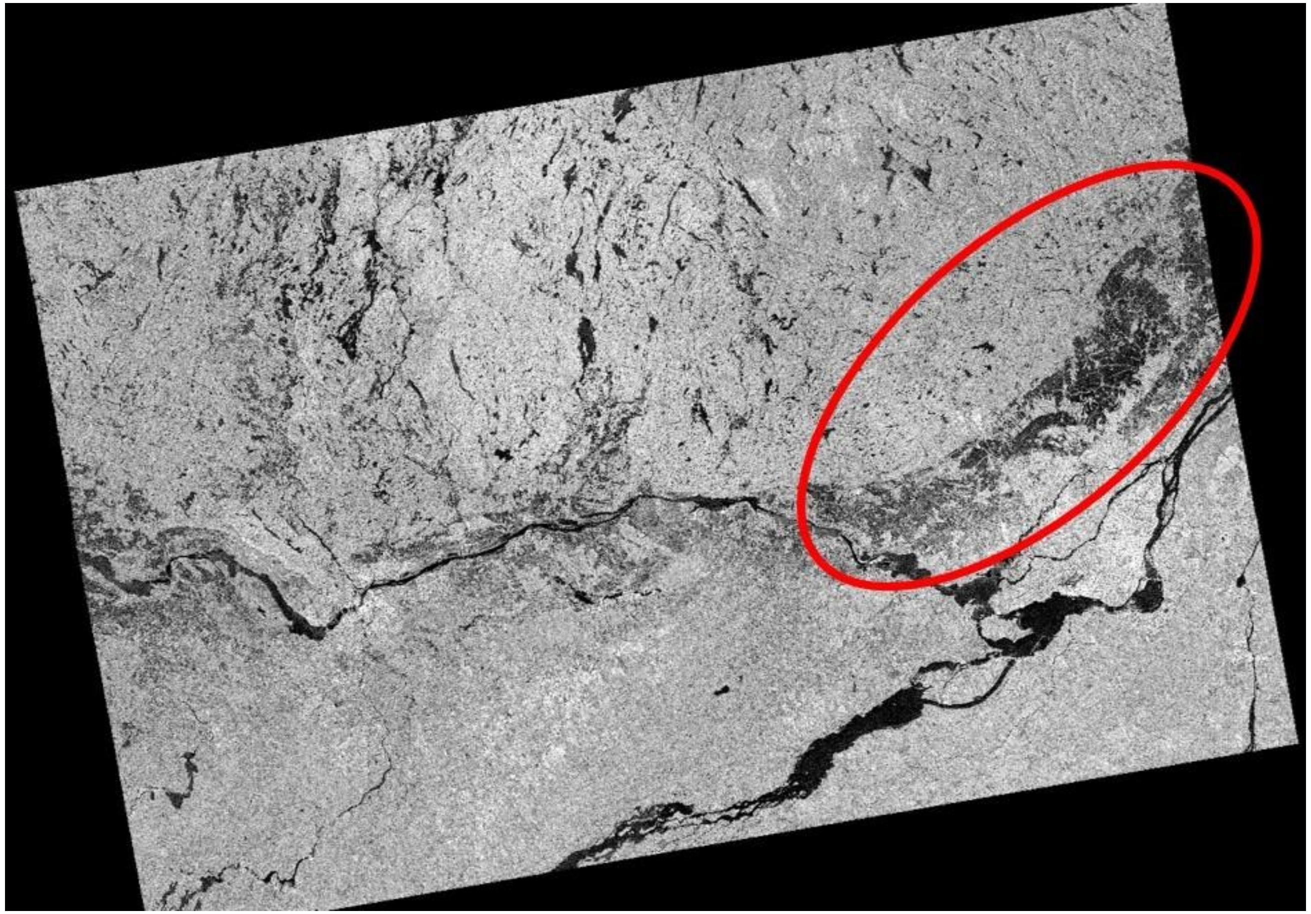
This is a simplified description of this phenomenon, because in reality the scattering problem is rather complex and depends on the liquid water content, density, snow grain size and superficial roughness.

As of today, there are no electromagnetic models available to model the complexity of the melting process and its influence on SAR backscatter.

To fill this gap, time series of SAR backscatter observations from the Sentinel-1 mission have been used to identify the beginning of the melting phase. Several studies referring to the utilization of satellite data for monitoring and mapping wet snow are available.

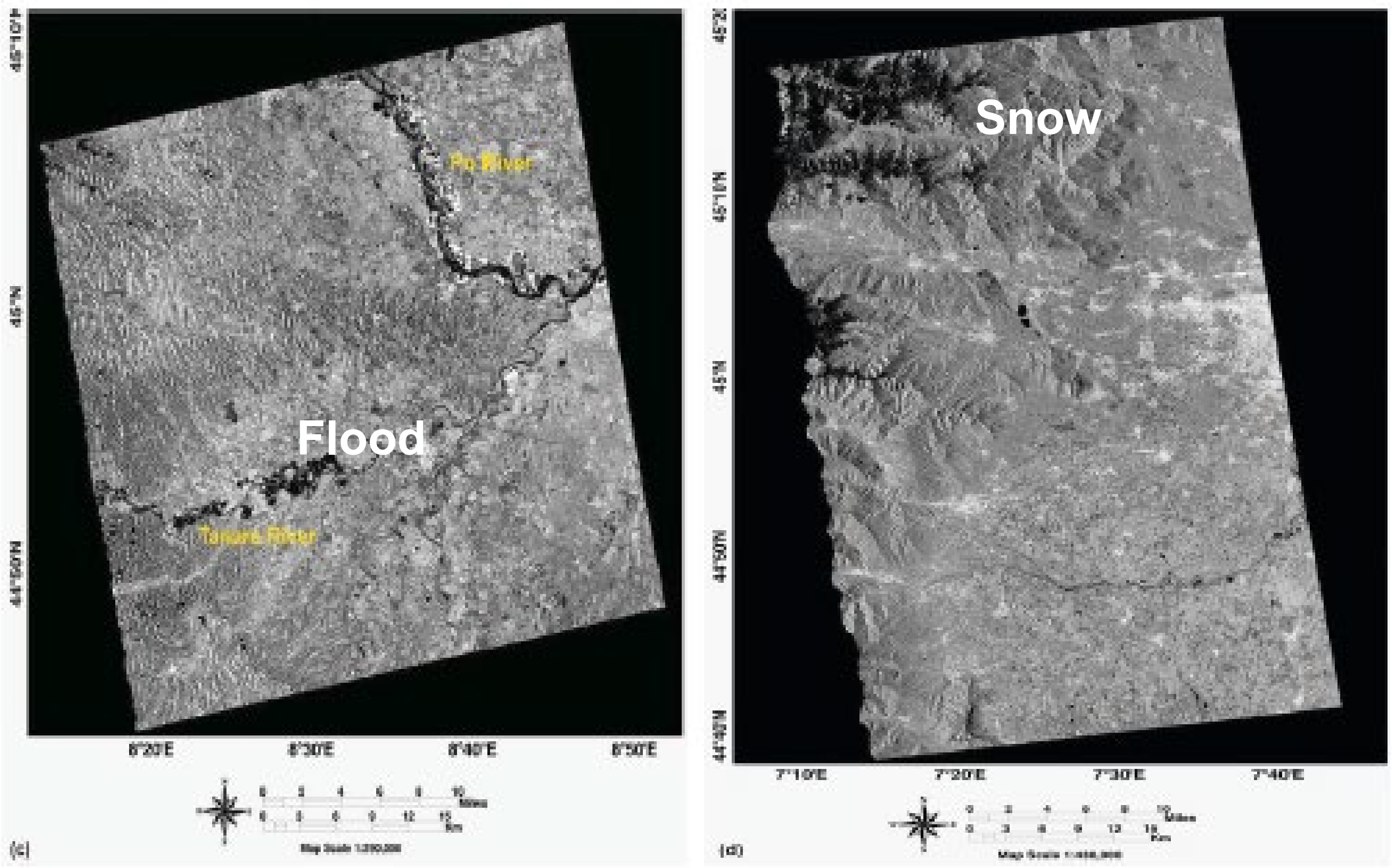
Snow

Sentinel-1 image acquired on 6/4/2019 over the Montreal area. The area depicted by the red ellipsoid corresponds to wet-snow and not water.



Snow

COSMO-SkyMed images, X-band sensor



Wind

Wind effects hampering any SAR-based mapping of floodwater extent is another well-known problem.

The contrast between backscatter from flooded and non-flooded terrain can be significantly reduced in the presence of strong wind roughening the water surface.

The effect typically leads to an underestimation of water bodies when applying commonly used retrieval algorithms.

The contrast between flooded and non-flooded terrain may even disappear completely in case of low moisture content and wind-roughened water surfaces.

Wind

So far, the radar scattering from rough surfaces affected by wind has been investigated only for the open sea, where the relationship between speed and direction of the wind and ocean waves is defined for well-developed sea and waves in equilibrium with wind.

However, the case of a flooded terrain is different and arguably more complex, since the number of unknowns is much higher, e.g. different water depths, obstacles obstructing the wind, etc.

In this situation, even in the presence of highly accurate meteorological information, the prediction of the radar signal would remain quite difficult.

Wind

Low frequency SAR data are less affected by roughness, so that the availability of L-band SAR observations and the development of adequate retrieval algorithms could help tackling the issue.

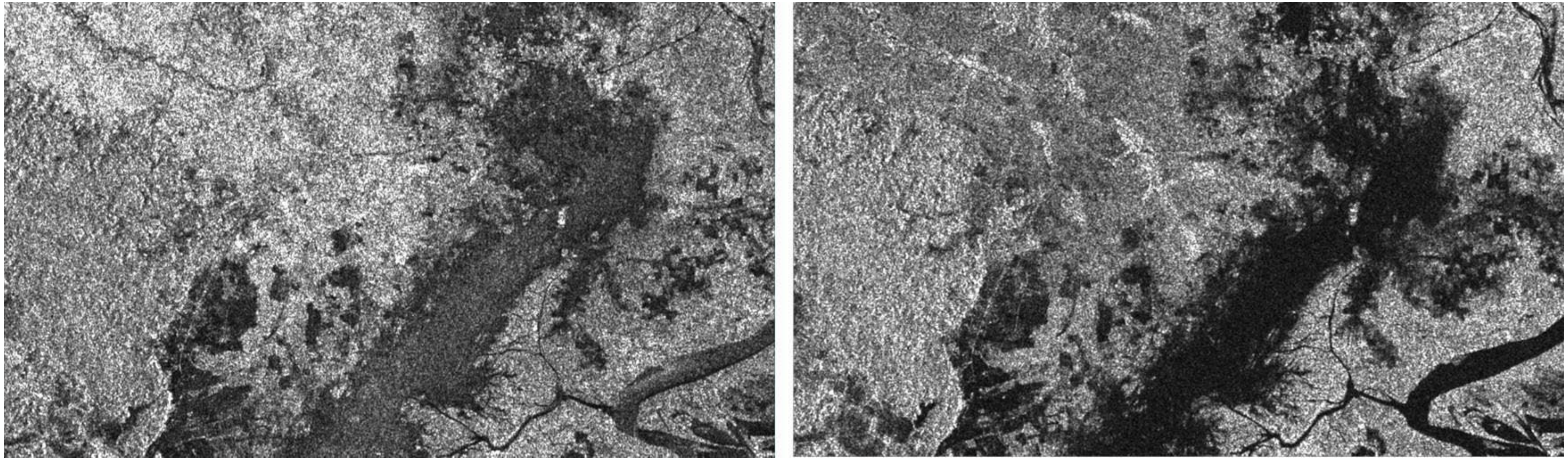
In addition, the availability of additional polarizations may allow improving the robustness of retrieval algorithms in such challenging meteorological conditions.

Cross-polarized data could provide an important contribution for detecting flooded areas under wind-induced roughness, since cross polarization is less sensitive to surface roughness.

Wind

Radarsat-2 image acquired on 3/8/2019 over Myanmar in HH (left) and HV (right) polarizations.

It is evident how wind over water surfaces affects differently co- and cross-polarized data.



Rain

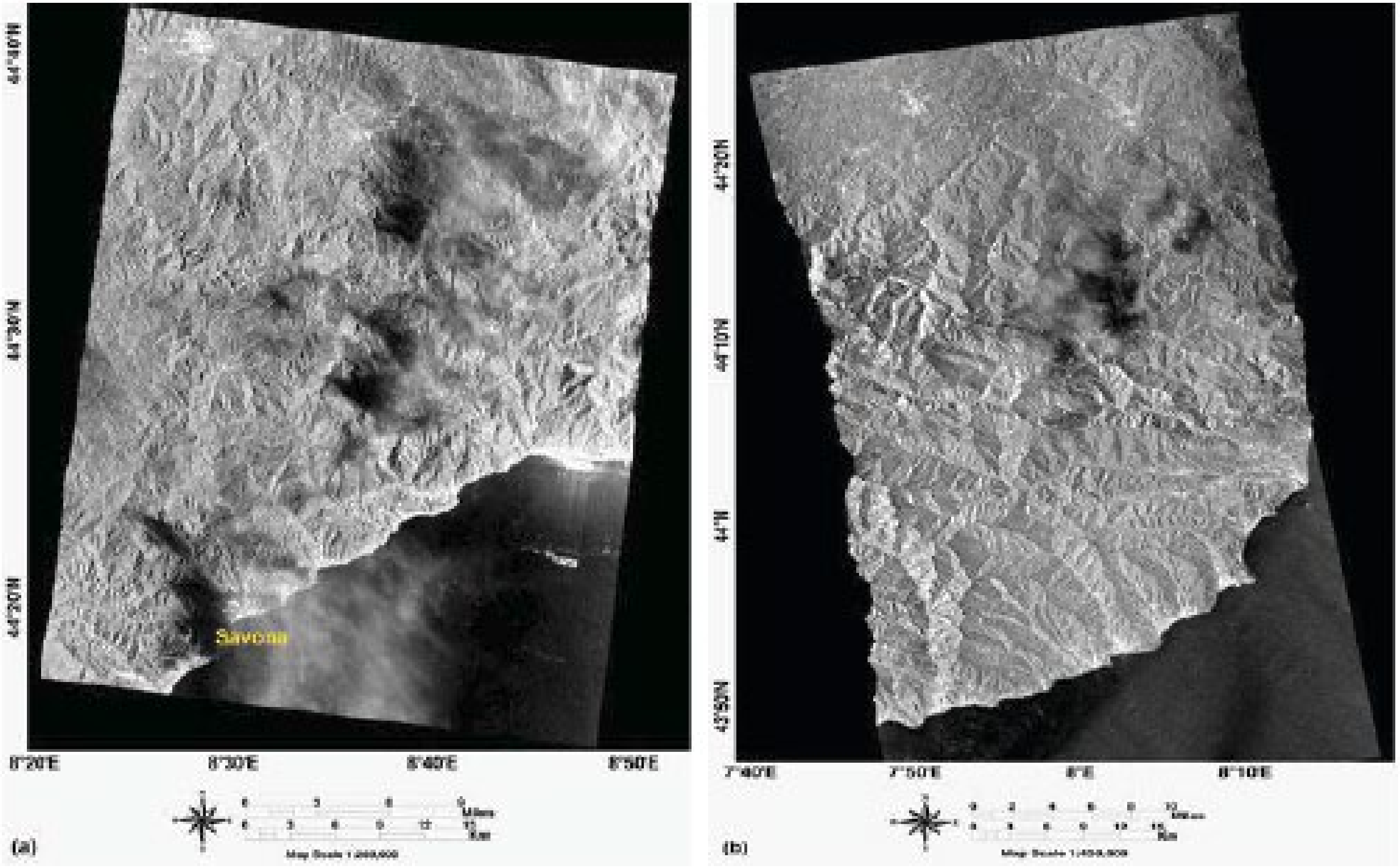
Differently from optical images, SAR sensors are commonly considered all-weather systems since for microwaves the atmosphere is quasi transparent.

However, it has to be considered that recent studies demonstrated that the high rainfall rates can be estimated from recorded satellite X-band SAR signal attenuations caused by rain cells.

As a matter of fact, when using SAR sensors for monitoring flooded areas, it is worth having in mind that with short wavelengths the attenuation of the radar signal due to heavy precipitation may be similar to that of surface water bodies.

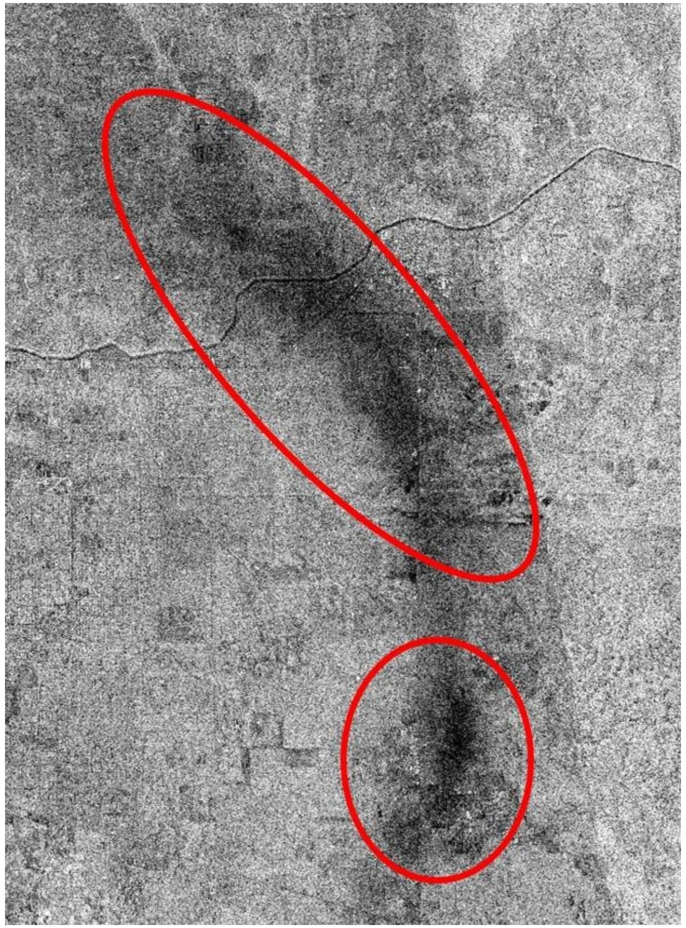
Rain

COSMO-SkyMed images, X-band sensor



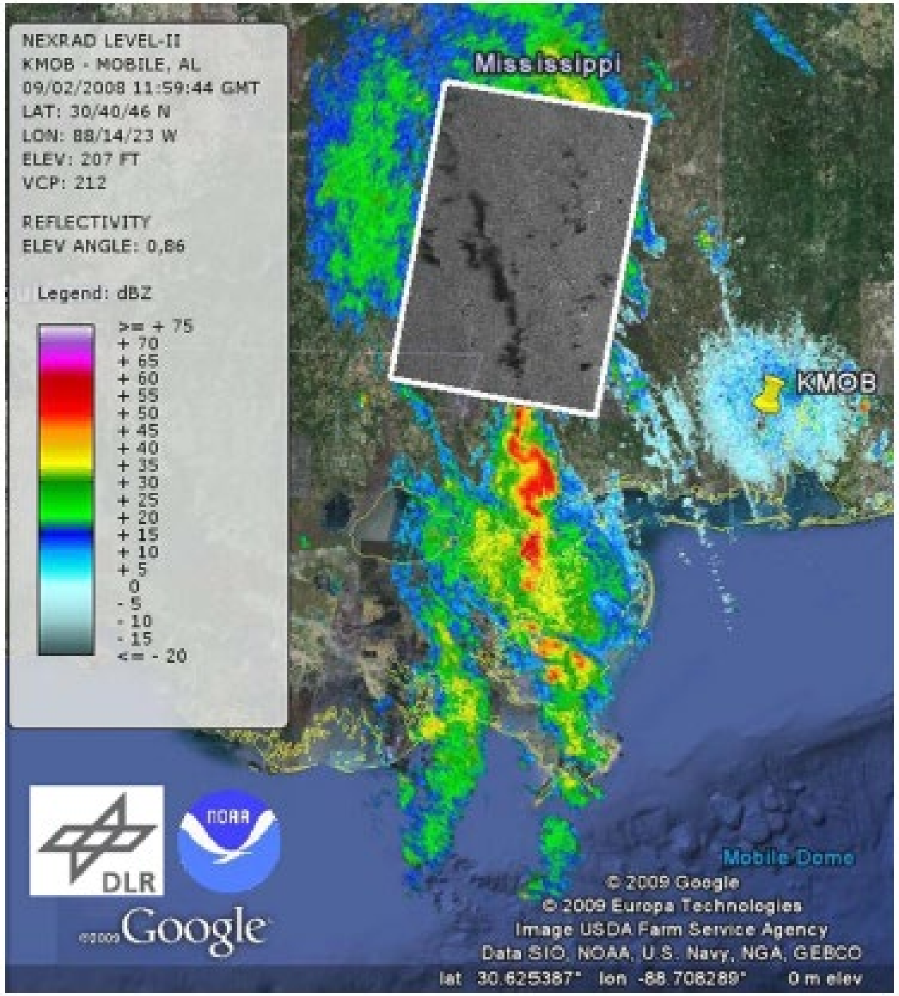
Rain

Sentinel-1 image acquired on 10/9/2017 during hurricane Irma. The areas depicted by the red ellipsoids represent the rain-cell attenuation.



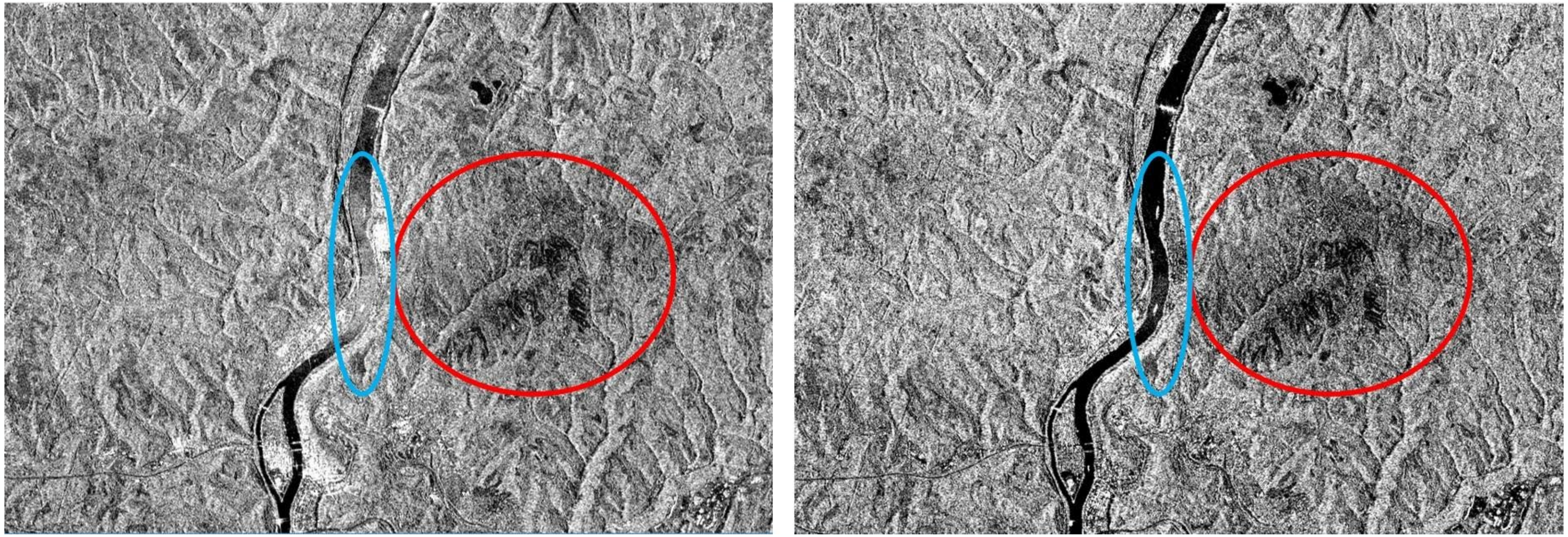
Rain

Comparison between S-band Weather Radar (WR) and TerraSAR-X satellite data



Rain

Moreover, precipitation has another important effect on open water that can be easily confused with wind, i.e. the roughening of water surfaces due to raindrops, which usually leads to an under-detection.



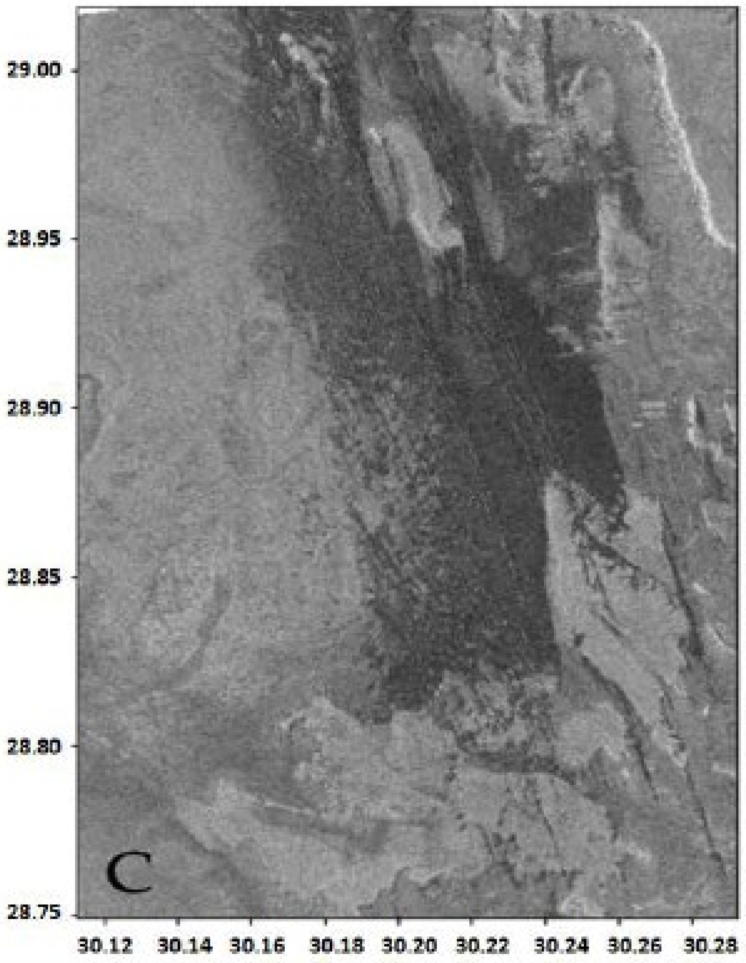
Sentinel-1 image acquired on 6/6/2016 over North Carolina during a strong rain event in VV (left) and VH (right) polarizations, where it is highlighted how the rain-cells attenuate the signal (red circle) and raindrops over water surface roughen it (blue ellipsoid).

Smooth surfaces

TerraSAR-X image, X-band sensor

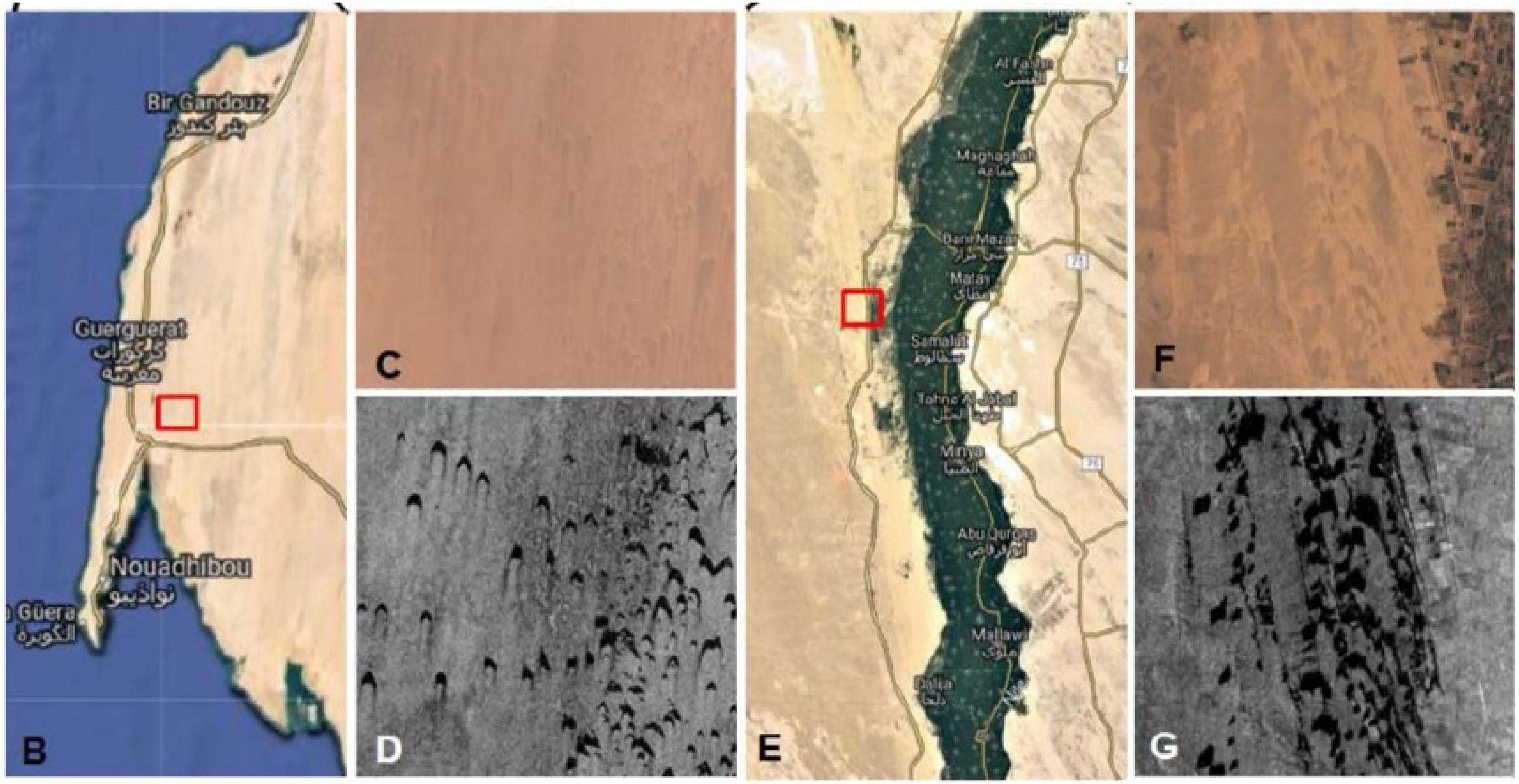
Arid areas – sand dunes

Sentinel-1 image, C-band sensor

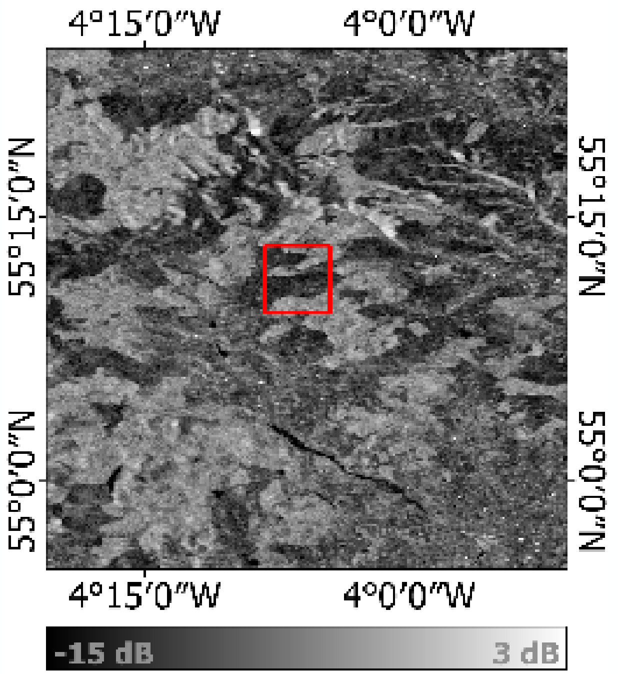


Arid areas – Sand dunes

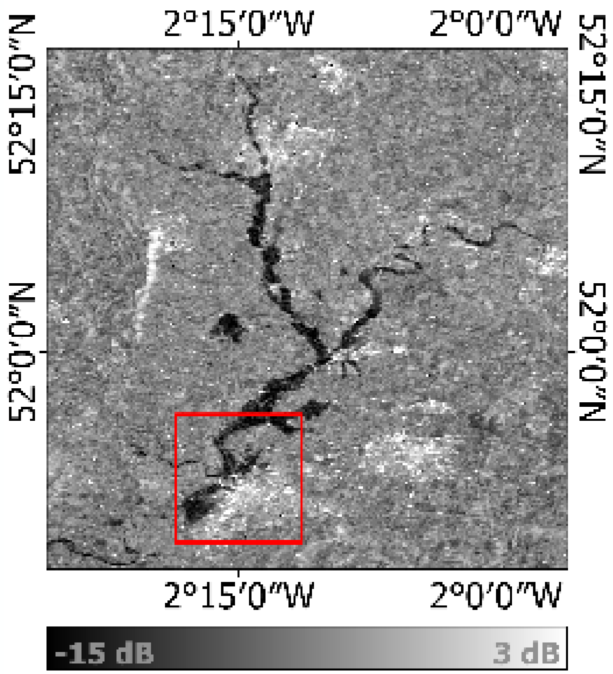
Sand surfaces are characterized as water look-alike areas, causing an overestimation of flood extent.



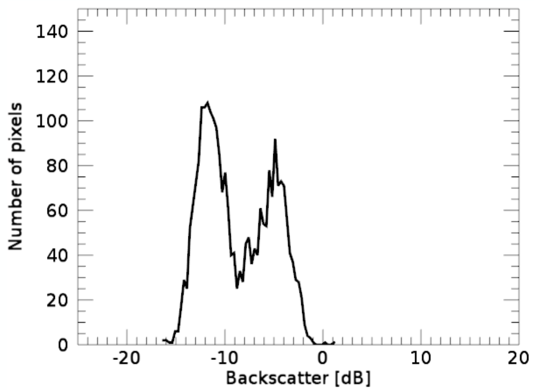
Vegetation



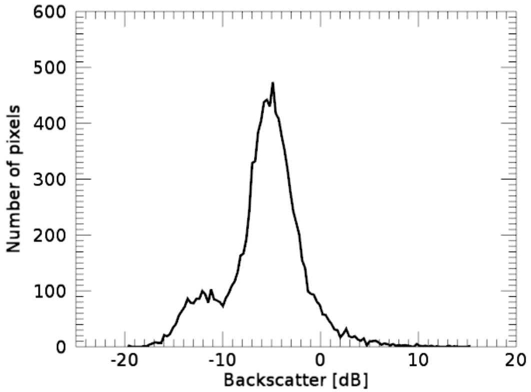
4°15′0″W
4°0′0″W
55°15′0″N
55°0′0″N
-15 dB
3 dB



2°15′0″W
2°0′0″W
52°15′0″N
52°0′0″N
-15 dB
3 dB



Number of pixels
Backscatter [dB]



Number of pixels
Backscatter [dB]

Flood mapping approaches: land covers

Depending on the different land covers, SAR-based flood mapping algorithms can be classified into three main categories:

- Bare soils or scarcely vegetated areas
- Vegetated areas
- Urban areas

Flood mapping approaches: number of images

Depending on the number of images used as input, SAR-based flood mapping algorithms can be clustered into three main categories:

- single image;
- dual image (i.e. change detection);
- multi-temporal sequences of images.

Single image

The identification of the water class is often performed by backscatter intensity. The detection of floodwater in SAR imagery is possible as backscatter from open calm water bodies is usually lower than that from the surrounding terrain.

Approaches to classify the water class:

- Thresholding,
- Segmentation
- Supervised classifiers

Single image

Advantages:

- highly efficient (fast)
- suitable for rapid flood mapping.

Drawbacks:

- False alarms caused by non-flooded land cover classes having water-like backscatter pixel values, such as smooth tarmacs, as well as very dry regions, wet snow, shadow regions and some of the vegetated areas. They can be solved using ancillary data such as shadow maps, land cover maps, DEM, etc.
- It is not possible to distinguish permanent water bodies from floodwater. A land cover map is needed to distinguish between the two.

Dual image (i.e. change detection)

These methods exploit the flooding-related decrease of backscatter with respect to a non-flood reference image, distinguishing transient floodwater from permanent water bodies.

Approaches to classify the water class:

- Thresholding,
- Segmentation
- Supervised classifiers

Dual image (i.e. change detection)

Advantages:

- highly efficient
- they overcome some of the shortcomings of single-image based methods (rather efficient for removing stable targets, such as tarmac, shadow areas, sand, permanent water bodies, etc.)
- suitable for rapid flood mapping.

Drawbacks:

- The selection of a reference image acquired under normal conditions (i.e. an image acquired not during the flood event) is a critical step since the accuracy of the final flood map depends on the reference data.
- Problems may still be present over vegetated areas characterized by seasonal cycles and periodically low backscatter due to absorption, especially at high incidence angles.

Multi-temporal sequences of images.

The use of multi-temporal SAR provides a means to better understand the seasonal behaviour of different land cover classes.

Approaches to classify the water class:

- Thresholding,
- Temporal indexes
- Supervised classifiers

Multi-temporal sequences of images

Advantages:

- Time series analyses allow discernment on whether a recorded low backscattering value is due to floodwater, or e.g. related to the phenological cycle of the vegetation class.
- The technique also provides advantages for identifying land cover classes that are prone to low backscattering, e.g. dry sand.

Drawbacks:

- They are demanding in data storage;
- Rely on the availability of SAR data obtained with high sampling rates, which is not always the case.
- They still struggle to correctly interpret anomalies that appear suddenly, such as those due to heavy precipitation/wind or snowfall.