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This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

Titles of pre-course Radar satellite basics

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1

Radar signal: phase and amplitude

A radar (radio sensing and ranging) device uses light in the radio range to measure the shape and distance of a target. The radar device emits pulses and records the echoes reflected by the target (backscattering), providing valuable information about it. These radar devices carry their own light source, which is why they are called active sensors, and are independent of external light conditions. In Earth remote sensing, the most common radar systems use microwaves, which correspond to the range between one millimetre and one metre on the electromagnetic spectrum.

The radar signal encloses the amplitude (A) and phase (Φ) parameters that can be represented in the complex reference system (Fig.1).

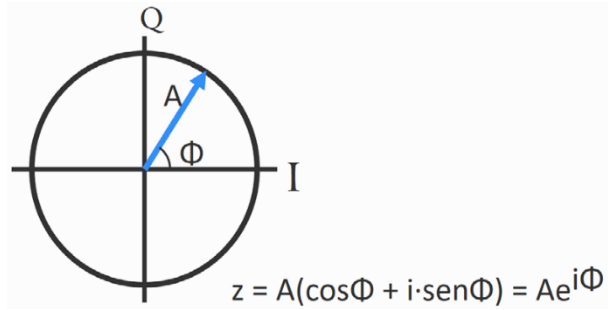


Figure 1. Radar signals are represented on the complex axes, which are usually called In-Phase (I), the real part, and Quadrature (Q), the imaginary part. The amplitude (A) is the module, and the phase (Φ) is the angle of the complex vector.

The radar device emits a monochromatic signal and measures the amount of energy, or amplitude, returning to the antenna, as well as the delay of this return, which is called phase (Fig.2). Thanks to its relatively long wavelength, microwaves can penetrate clouds and smoke, and because radars are active sensors, they can also record at night. The amplitude informs us about the shape and dielectric property of the target; thus, the amplitude component can be used to classify terrains, to map land use, wildfires, moisture and water bodies, among others. The phase, in turn, refers to the backscattering delay relative to a baseline, representing a measure of distance to the target. The phase difference (ΔΦ) between two satellite images taken from two different positions at the same time is used to build Digital Elevation Models, like the SRTM, which are 3D representations of the Earth's surface. On the other hand, the phase difference between two satellite images taken from the same positions at different times is used to measure ground deformation.

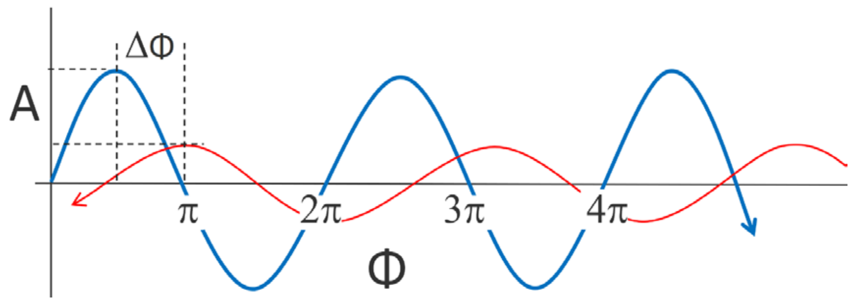


Figure 2. The amplitude (A) and the phase differences (Φ) of the emitted (in blue) and returned signal (in red). In this particular case, the phase difference (ΔΦ) is equivalent to π/2.

2

Synthetic Aperture Radar, SAR image formation

The resolution of a radar satellite depends on the duration of the emitted pulse (the shorter the better) and the length of the physical antenna (the longer the better). Resolution is improved by using a compressible pulse and by stretching the antenna through the combination of all antenna positions that illuminate a single scene. The latter is called a synthetic antenna and that is why the technique is called Synthetic Aperture Radar, SAR.

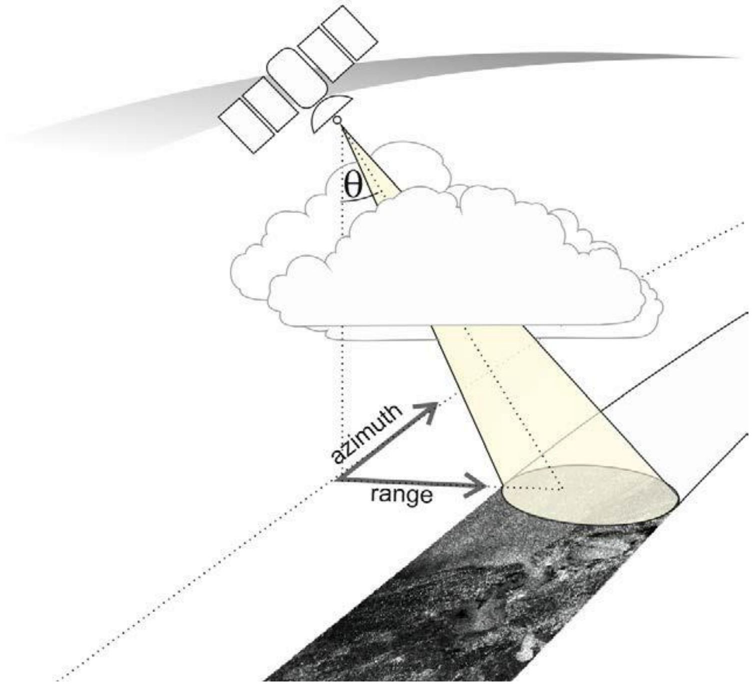


Figure 3. Satellite radar acquisition. It can penetrate clouds to build an image from the echoes of its emitted signal. The radar satellites are side-looking, meaning that the beam is emitted with an angle, called incidence angle (θ). The image is formed in the azimuth-range reference system.

As a radar satellite moves forward emitting and receiving echoes, a complex image is generated. This image contains the amplitude and phase of every pixel of the footprint (Fig. 3). The reconstruction of the image from the recorded echoes is done in the azimuth-range reference system. The Azimuth axis is the direction along the travel track, which is the path of the sensor moving around the orbit. The Range axis is the direction across the satellite track and it indicates the route of the beam. The beam, in turn, is emitted at a certain angle, incidence angle (θ), which is necessary to break symmetries and allow the image to be formed from radar echoes. The formation of SAR images requires the integration of several parameters such as the orbit, the beam aperture, the beam footprint, the echo delay, the Doppler effect and the amplitude.

The image resolution is the ability to discriminate between two different targets. The resolution in range is improved by using a chirp pulse that is later compressed up to 2 order of magnitude (the shorter the better). To improve azimuth resolution, the antenna is synthetically stretched (the longer the better) by combining all antenna positions that illuminate a single scene (Fig. 4). Sentinel-1's real 10-metre antenna (providing an original resolution in azimuth of 5 km) can be synthetized into a 2.5-km antenna, which means magnifying it 250 times. Thanks to these focusing techniques a Sentinel-1 image has a resolution of 5 m in range and 20 m in azimuth.

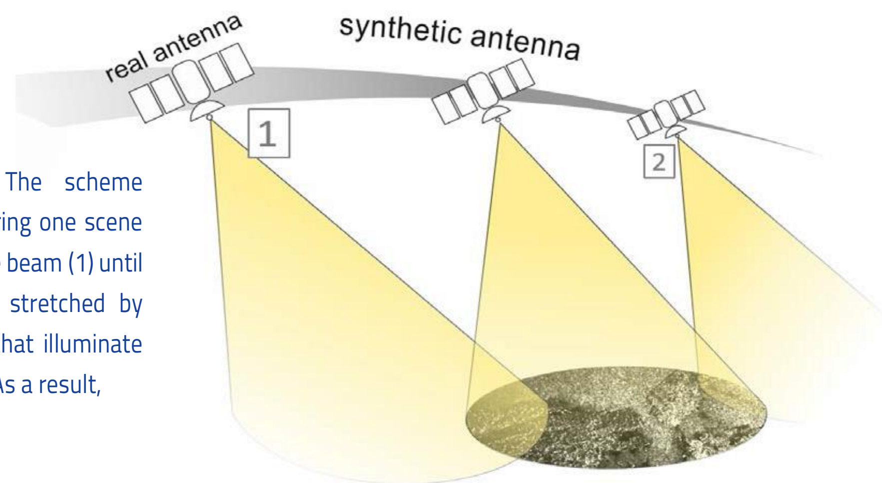


Figure 4. Synthetic antenna. The scheme represents a radar satellite capturing one scene from the moment that it enters the beam (1) until it exits (2). The real antenna is stretched by combining all antenna positions that illuminate the scene between point 1 and 2. As a result,

It is important to point out that, since the Earth is rotating while the satellite is orbiting, the same scene is imaged twice in the same cycle: the first image is taken when the satellite is ascending South-North and the second one when the satellite is descending North-South (Fig. 5). This characteristic is relevant because it provides two perspectives of the same area, producing two complementary images of the same scene.

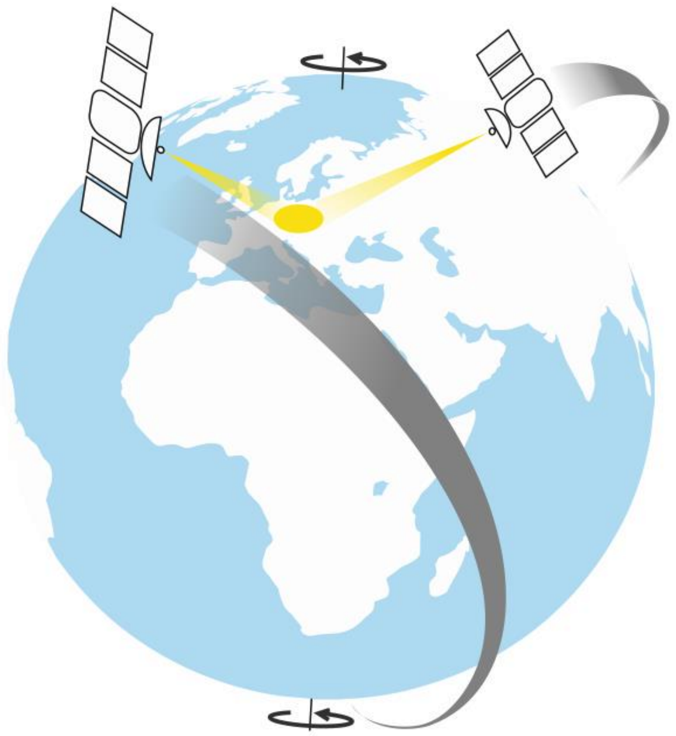


Figure 5. Taking advantage of the Earth's rotation, the radar satellite takes two images of the same scene: one when the satellite is ascending and the other when it is descending. This sketch represents the two acquisitions simultaneously, but they are actually 12 hours apart in Sentinel-1's case.

The main advantages of SAR images are that they can:

- Image the Earth's surface in all weather conditions even at night.
- Provide information about Earth's surface texture and structure.
- Penetrate canopy and even soils under special conditions.
- Be sensitive to moisture in soil and vegetation.
- Measure distance, which means the ability to map topography and to measure ground displacements.

The main limitations of SAR images are:

- They are difficult to interpret.
- Complex processing is required.
- Radiometric and geometric distortions are not always possible to be corrected.
- Signal decorrelation in surface is in permanent transformation, preventing displacement measurement.

3

Radar parameters and backscattering mechanisms

Radar signal and target interaction is a complex process involving several parameters. Understanding this interaction is essential to uncover the backscattering mechanisms that generate our radar image.

Radar signal and target interaction is a complex process involving several parameters. The backscattering has a signal dependence and a target dependence. The parameters playing important roles related to the signals are (Fig. 6):

1. The wavelength: the longer the wavelength the greater the penetration but the lower the resolution.
2. The incidence angle: the more vertical the higher the penetration and the better the signal return.
3. The polarization: Radar devices usually emit light in vertical (V) or horizontal (H) polarization and can thus receive vertical or horizontal polarization back. Thus, the following combinations are possible: VV, HH, VH, and HV. The last two are called cross-polarizations. Band relationships between the different polarizations can be established to extract information about the target.

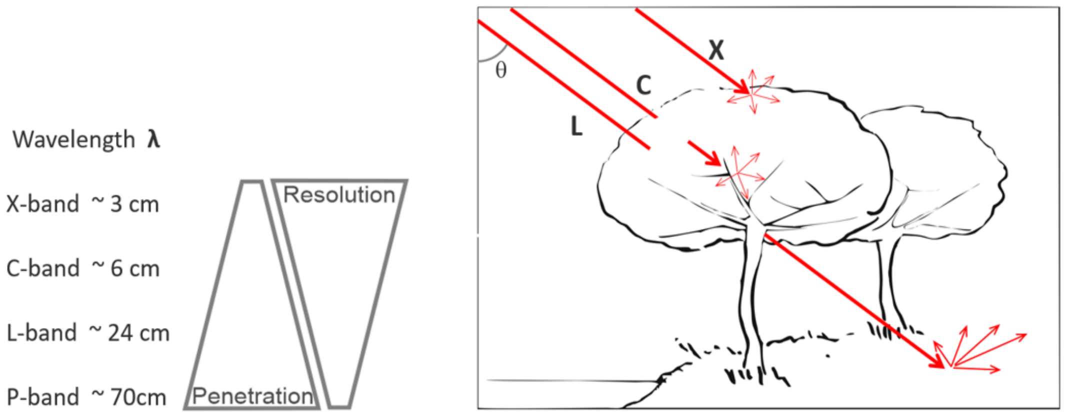


Figure 6. The common microwave bands on satellites and a representation of their penetration capacity. The longer the wavelength, the higher the penetration and the lower the resolution. The incidence angle (θ) also plays an important role in the interaction of the signal with the target.

The relevant parameters related to the target are (Fig. 7 and 8):

4. The roughness: the higher the surface roughness the higher the backscattering.
5. The structure: specific lineation or configurations can favour backscattering.
6. The dielectric constant: it quantifies the tendency of a material to polarize opposing the passage of an incident electromagnetic signal. The higher the dielectric constant, the lower the signal penetration and thus, the stronger the scattering. Water has a dielectric value of almost an order of magnitude higher than the typical dry materials on the ground surface. Therefore, water plays an important role in the signal's ability to penetrate vegetation and soils. This property can be used to measure relative moisture in sediments or mining waste.

The scattering that occurs within the treetops is called volume scattering (Fig. 6), and it is produced by the multiple random bounces between the leaves, branches and trunk. The resulting image of these areas is clear and homogeneous. Furthermore, cross-polarization is favoured since the signal depolarizes with each bounce. Other backscattering mechanisms are shown on Figure 7 and 8.

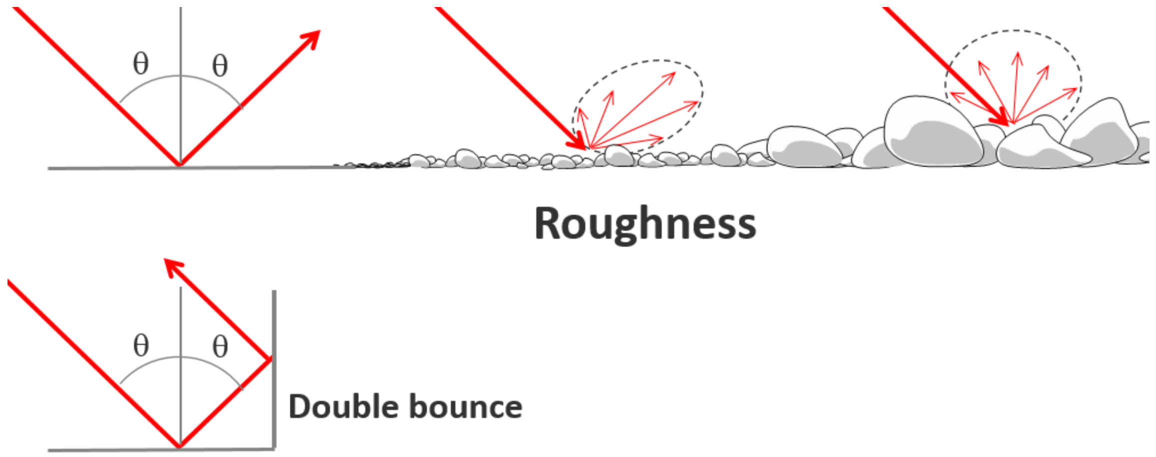


Figure 7. Above, the relationship between roughness and the backscattering mechanism is shown. If the surface is very smooth compared to the wavelength, the signal is reflected away, like in a mirror, therefore there is no backscattering and the image appears black. This is typical in water bodies. As roughness increases, the scattering spectrum also increases, and more energy is reflected back to the sensor, thereby increasing the brightness of the image. Below, the double bounce effect, which consists of strong backscattering produced in the corner between floors and walls, resulting in a very bright image; it is common in urban areas, and also in tree trunks that are close to open water

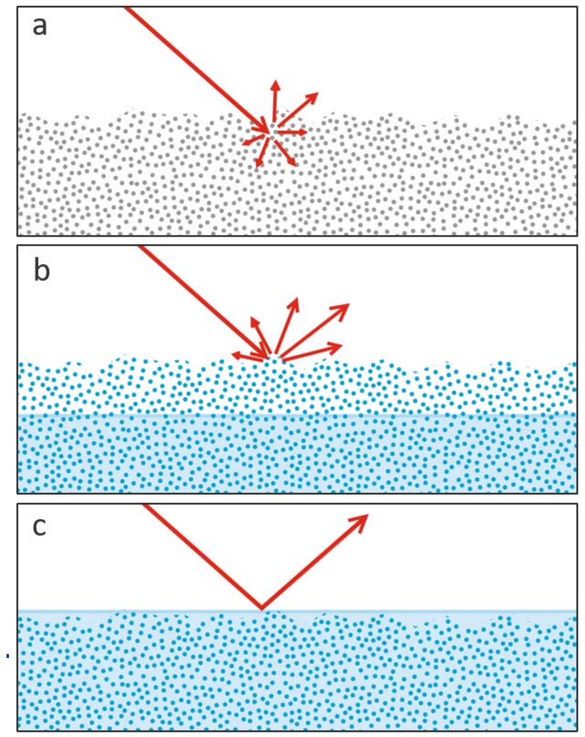


Figure 8. the water content of a target plays a determining role in the backscattering mechanism. The scattering behavior of a terrain greatly depends on the moisture degree: a) the radar signal has the ability to penetrate in dry and unconsolidated soils; b) the dielectric constant of the ground increases with humidity, reducing penetration and improving backscattering; c) when the ground is flooded, the mirror effect occurs and all the incident energy bounces away.

4

Radar distortions

The distortions that a radar signal undergoes in its round trip after interacting with a target are of great relevance for the image interpretation. These distortions are inherent in the formation of radar images from the echoes of a coherent signal. In order to extract reliable information from an image, these distortions have to be corrected to the extent possible.

The process of radar image formation brings about some distortions that have to be corrected in order to extract reliable information from the images. They can be divided into two types: the radiometric distortions (specific to the signal and the sensor), and the geometric distortions (specific to the acquisition geometry and topography).

The main sources of radiometric distortion are signal interferences, signal loss, non-uniformity of the synthetic antenna, or saturation of the sensor. The most common radiometric distortion observed in radar images is this typical granular texture, called "speckle". This type of noise is caused by the interference of coherent echoes within a pixel. More precisely, after multiple bounce off before returning to the sensor, the interfering echoes could be no longer in phase and, consequently, some constructive or destructive interferences can occur, causing that typical bright and dark pixel texture. Correcting this distortion is necessary for the proper identification of the target and for statistical analysis of the image.

The side-looking geometry of the satellite is necessary to break the incidence symmetry and to provide differentiation between the echoes in range direction. However, this geometry causes distortions when forming the radar image. The radar satellite emits signals and receives the backscattering after the interaction with Earth's surface. As the antenna records echoes, the image that is formed depends more on the distance of the satellite-reflectors than on the shape of the ground. Therefore, depending on the geometric configuration between the topography and the incidence of the beam, some distortions can occur (Fig. 9):

1. There is not distortion when the Line of Sight (LOS, the direction connecting sensor and target) is parallel to the local slope.
2. Foreshortening is produced when the local slope faces the LOS. As a consequence, in the radar image, the slope looks bright and shorter.
3. Layover is produced in very steep topographies, when the summit of a mountain is closer to the satellite and therefore its echoes arrive before those from the foothill. The mountains appear inverted in the radar image.
4. Shadow occurs in the unilluminated back-slope, and no information can be retrieved.

When the incidence is vertical, the foreshortening is extreme and it is not possible to differentiate between reflectors; all the echoes arrive at the same time. This is why radar satellites look from the side, to break symmetries. However, the occurrence of shadow increases with the angle of incidence and this is why imaging the scene from two geometries (ascending and descending) is relevant. The incidence angle of Sentinel-1 varies between 18.3° (near range) and 46.8° (far range), but the topography determines the local incidence, and therefore the final geometry. For an accurate interpretation, geometric distortions have to be corrected, for which a digital elevation model is used on which the different echo sources are located. When geometric distortions are too severe, it is not possible to differentiate the echoes from each other and the correction is thus not possible.

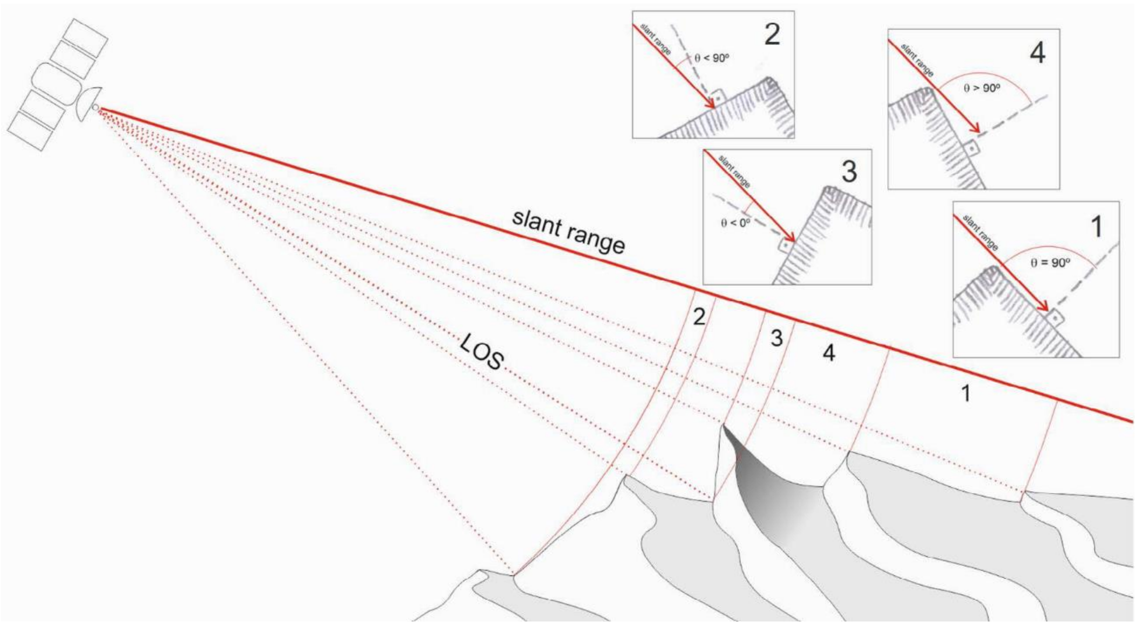
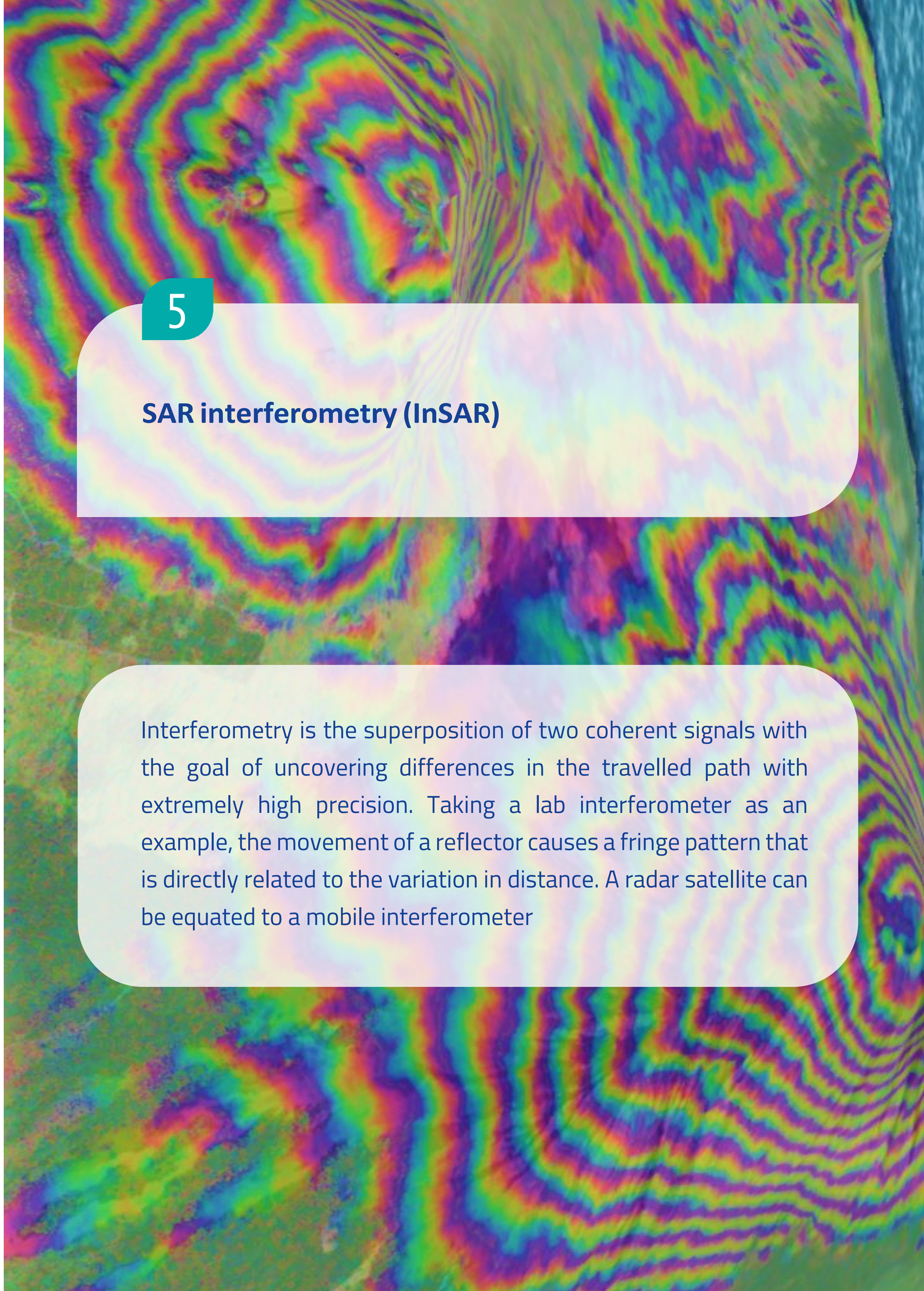


Figure 9. Scheme of the acquisition geometry of a radar satellite. The satellite looks at the Earth's surface from the side with range of incidence angles associated with the beam aperture, but it is the topography which determines the local incidence. The arcs that cut the Line of Sight (LOS) connect points of equal distance to the sensors, the echoes arrive from them at the same time. No distortion occurs at the configuration number 1, when slope is parallel to LOS; foreshortening occurs at number 2 when slope faces LOS; layover occurs at number 3; and shadow at number 4.



5

SAR interferometry (InSAR)

Interferometry is the superposition of two coherent signals with the goal of uncovering differences in the travelled path with extremely high precision. Taking a lab interferometer as an example, the movement of a reflector causes a fringe pattern that is directly related to the variation in distance. A radar satellite can be equated to a mobile interferometer

The phase differences between two SAR images produce a map of fringes called interferogram that can be translated as differences in distance between the sensor and the Earth's surface. In this way, measuring the phase differences between two images taken at the same time from different perspectives allows us to build digital elevation models (DEM); as the SRTM and TanDEM-X spacebornes did. On the other hand, measuring the phase differences between two images taken from the same position in different periods of time allows measuring the ground deformation that occurred between the two acquisitions (Fig. 10). The accuracy in measuring distance is linked to the ability to measure phase differences; thus, in the case of microwaves, it is possible to measure displacements of a few millimetres within a pixel. Therefore, the InSAR technique is a precious tool for monitoring ground stability. It is important to note, however, that the displacement can be measured only if the signal is preserved, that is, only when the surface reflectors are preserved, as in subsidence or uplifting processes, but not when the surface is deeply transformed, as after a collapse. This means that satellite radars can be used, for example, to measure the displacement between blocks produced by an earthquake, the swelling of an active volcano, or movements in a dam that can anticipate a disaster, among others.

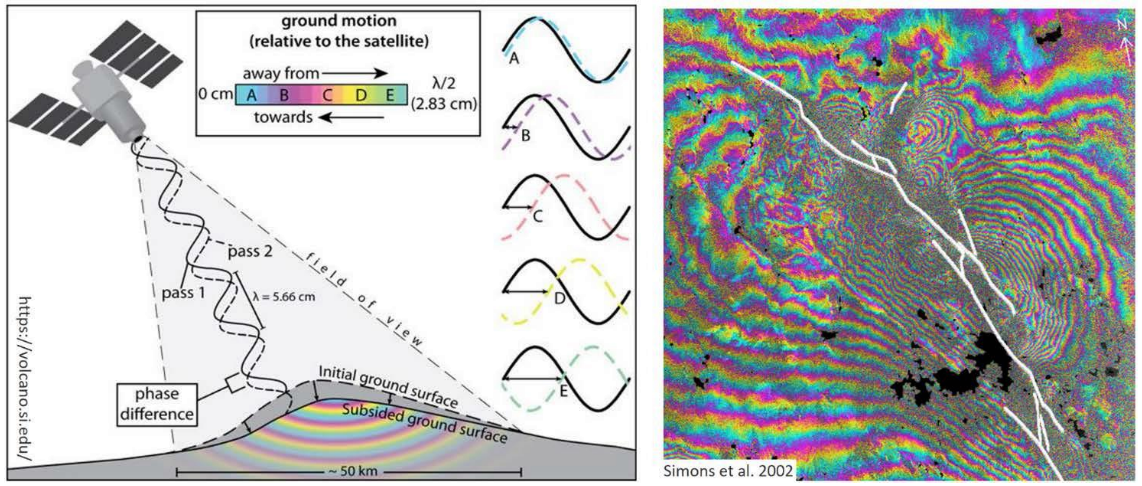


Figure 10. The sketch on the left shows the formation of interferometric fringes produced by phase differences between 2 image acquisitions (pass1 and pass2) as a consequence of ground subsidence. The sensor is a C-band and, as a result, a fringe cycle (from blue to blue) is equivalent to a displacement of around 3 cm. The image on the right is the interferogram of an earthquake resulting from two radar images (before and after the event). The displacement is so big that other contributions to the phase are negligible. You can evaluate the displacement by counting fringes (ERS satellite, also a C-band).

When the displacement is big, e.g. the displacement produced by an earthquake, it can be measured using only two images. But when measuring very small displacements, like the settlement of a waste dump, there are other contributions to the phase difference that mask the displacement contribution and they have to be removed. These are the atmospheric, the topographic, and the noise contributions. The following equation describes the different contributions to the phase difference ($\Delta\Phi_D$) between two radar images:

$$\Delta\Phi_D = \Phi_{image2} - \Phi_{image1} = \Delta\Phi_{disp} + \Delta\Phi_{topo} + \Delta\Phi_{atm} + \text{noise}$$

The atmospheric ($\Delta\Phi_{atm}$) and topographic ($\Delta\Phi_{topo}$) contributions can be modelled and removed. Therefore, the displacement contribution ($\Delta\Phi_{disp}$) can be calculated by removing noise. The main sources of noise are residues from the atmospheric and topographic correction, orbital errors, instrumental noise and signal decorrelation. The random noise is removed through data redundancy, that is, through the interference of a large number of image pairs of the same area during a given time period. Processing a large number of radar images demands extensive storage capacity and exceptional computer resources. To illustrate, let us look at an example of the stability study carried out in the Riotinto mine (Fig. 11). This study used 33 Sentinel-1 images, each of 5GB, 199 interferograms were generated, and all the processing required 40 hours on a powerful server.

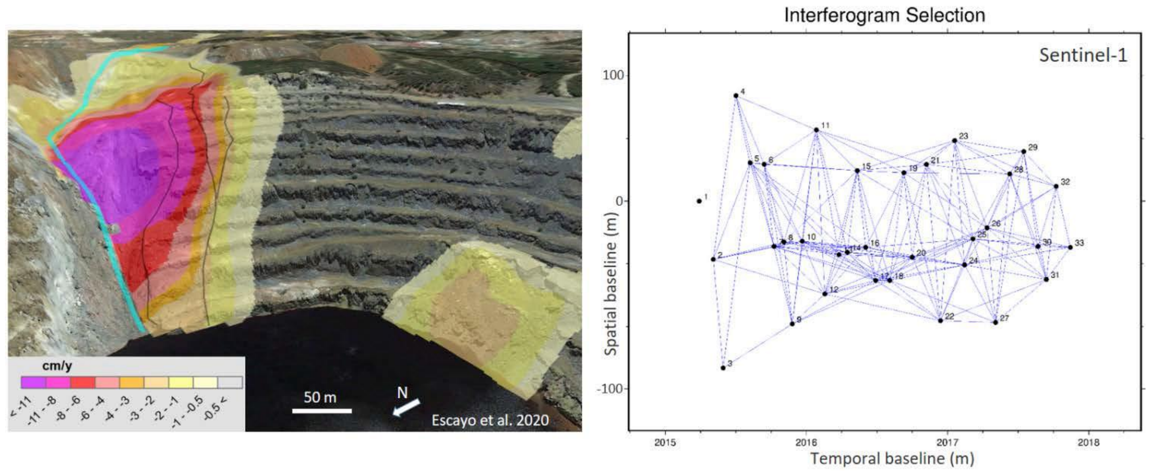


Figure 11. The image on the left shows the displacement along the slope in a weakened wall of the abandoned pit in the Riotinto Mine. The displacement velocity is measured in centimetres per year. The graph on the right is a cloud of interferograms. Each point represents a radar image placed according to its temporal baseline in the horizontal axis (when it was acquired), and its spatial baseline in the vertical axis (the position of the sensor in the orbital tube when the image was acquired). The blue lines represent the interferograms calculated for the analysis. Sentinel-1 is a satellite with very small baselines, which is helpful because it reduces signal decorrelation

6

Sentinel-1 imaging

The primary objective of Sentinel-1 is to monitor land and ocean with data continuity around the planet. This means that it is a satellite of medium resolution but with the advantage of providing free frequent images of any site on Earth. There are other satellites of higher resolution such as TerraSAR-X or COSMO-SkyMed, but the images are served on demand and at a high price. Sentinel-1 constellation is composed of two satellites (A and B) in opposite positions in orbit, which allows a new image of the same scene every 6 days. If we take into consideration that the image footprints are overlapped and that in some areas of the planet, e.g. Europe, Sentinel-1 provides ascending and descending images, we have more than 10 images of a site available per month in the Copernicus Open Access Hub.

https://scihub.copernicus.eu/dhus/#/home

Sentinel-1A was launched in April 2014 and Sentinel-1B in April 2016, and catalogue images are available since then. The Sentinel-1 sensor operates in four different modes: Stripmap (SM), Interferometric Wide swath (IW), Extra Wide swath (EW), and Wave mode (WV). The main operating mode is the IW, which acquires images at 5 x 20 m full spatial resolution and 250 km swath, and it is the mode that will be used in this course. You can find more details about acquisition modes in the ESA website.

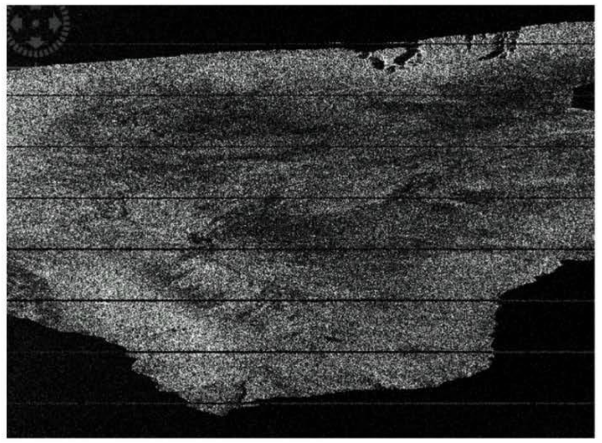
https://sentinel.esa.int/web/sentinel/user-guides/sentinel-1-sar/acquisition-modes

The images are provided at different processing levels. We are interested in the Level-1 because it corresponds to the focused images. There are two types of images in Level-1: Single Look Complex (SLC) and Ground Range Detected (GRD) (Fig. 12). The SLC consists of single look complex values (I and Q) that allow us to determine amplitude and phase in the slant range projection. The image is divided into 3 swaths and 9 bursts. On the other hand, the GRD indicates only amplitude values, the images are multi-looked (square pixels of 20x20m) and projected to the ground range using the Earth ellipsoid WGS84. In this course we will only work with GRD images since working with phase is beyond the purpose of this introductory course. For more details, please check ESA website.

https://sentinel.esa.int/web/sentinel/user-guides/sentinel-1-sar/product-types-processing-levels

	Mode	Type	Bands	Phase info	Projection	Composition	Look
Level-1 focused	IW VV & VH 250 km	SLC	real & imag.	Yes	Slant range	Swaths & burst	Single 1 x 1 ~ 5x20 m
		GRD	real	No	Ground range	merged	Multi 5x 1 ~ 20x20 m

Hawaii: Sentinel-1 SLC 2018/05/29 IW2



Sentinel-1 GRD 2018/05/29

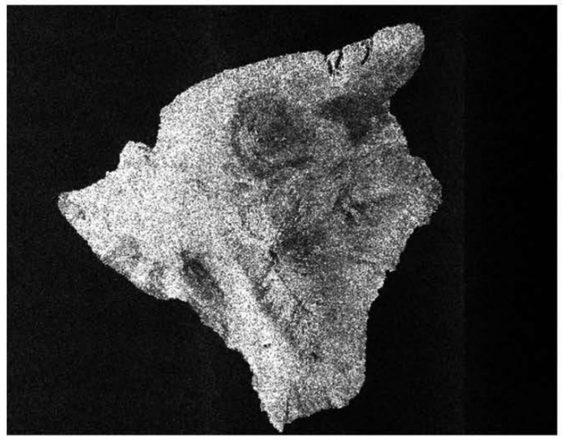


Figure 12. Table with main characteristics of both SLC and GRD Sentinel-1 images. The image on the left is the second swath of the SLC image of Hawaii, the horizontal lines corresponds to the limits between bursts. The image on the right is the GRD from the same acquisition.

Finally, it is important to pay attention to the image naming convention, as it provides relevant information about the dataset. Figure 13 highlights the main parameters to be considered when dealing with Sentinel images, such as satellite, acquisition mode, type, and date and time of acquisition.

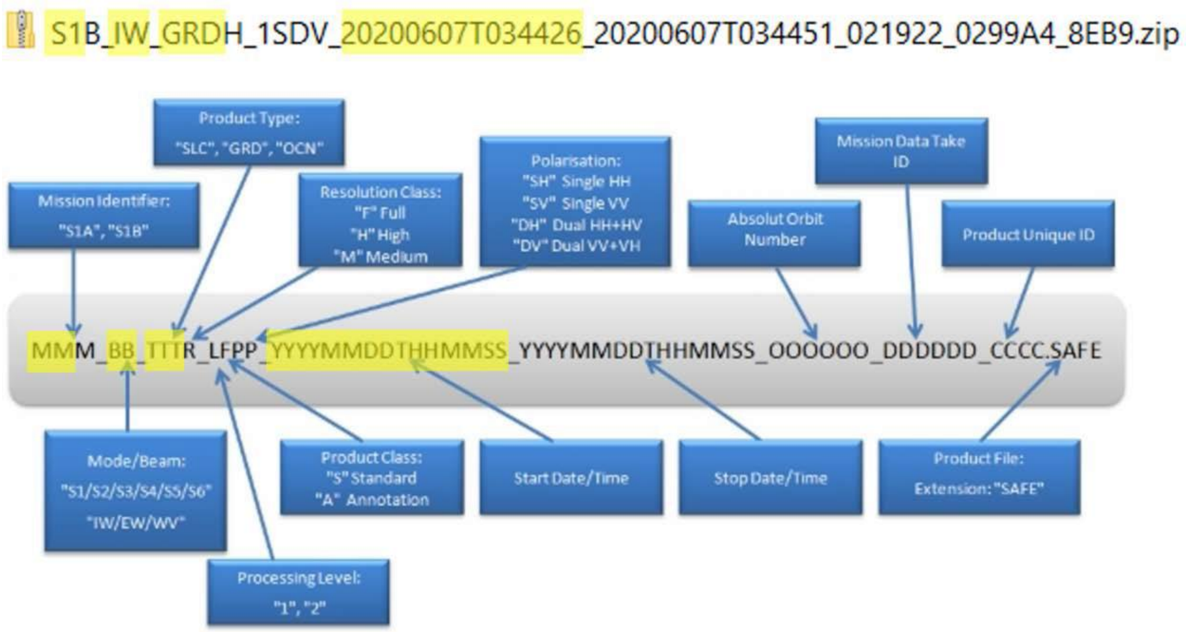


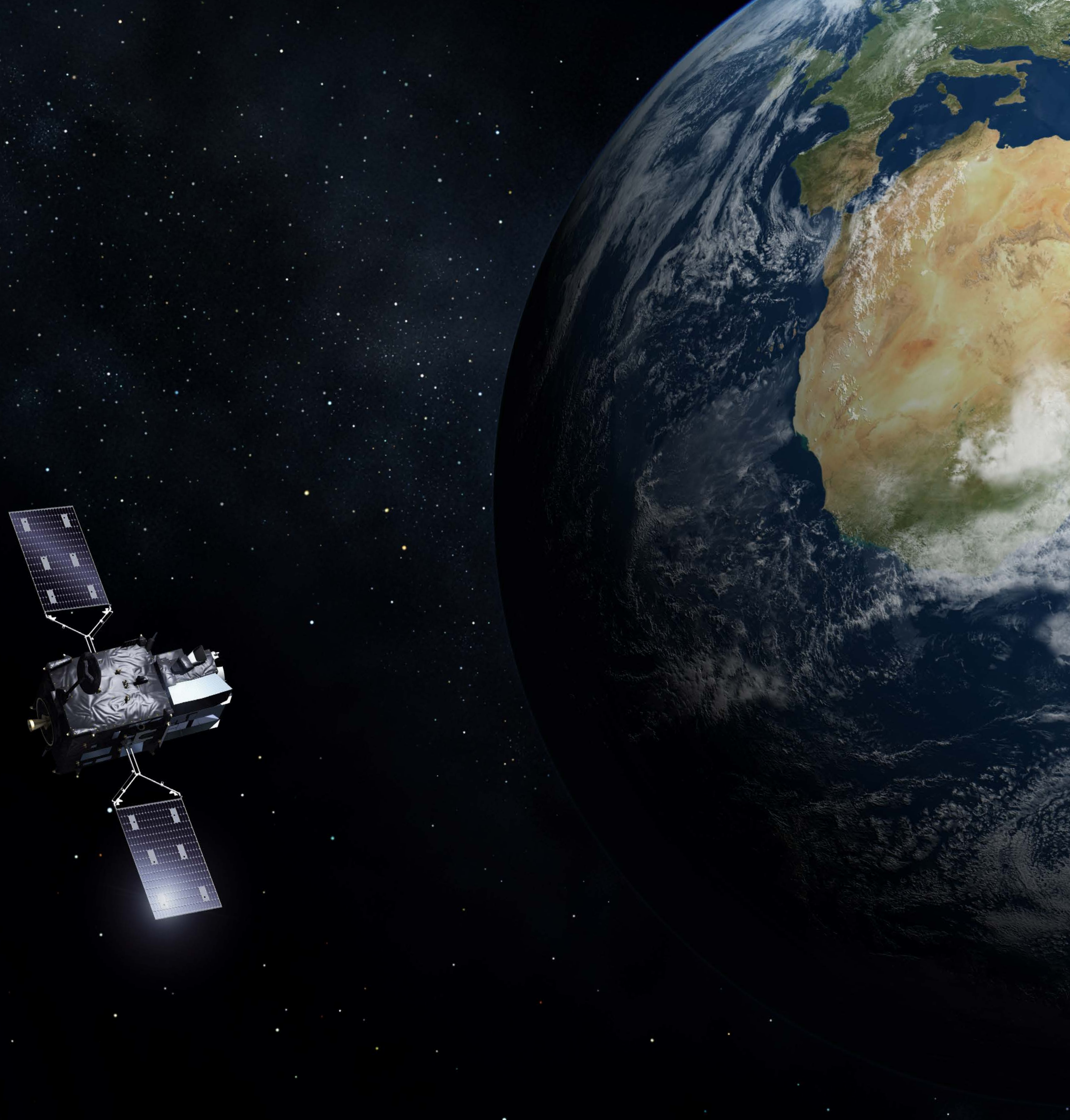
Figure 13. Sentinel image, name convention.

References

Courses and tutorials: ESA; ARSET (NASA); RUS (Copernicus); COMET; EO College

Open software: ISCE (Caltech/JPL & Stanford); ROI-PAC (Caltech/JPL); GMTSAR (SIO & SDSU); DORIS (TU-Delft); StaMPS (U. Leeds); LiCSAR/LiCSBAS (U. Leeds); SNAP (ESA)

Commercial software: Gamma; SARScape (ENVI); DIAPASON (Altamira); IMAGINE (Erdas)



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This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation