MICROWAVES and RADAR

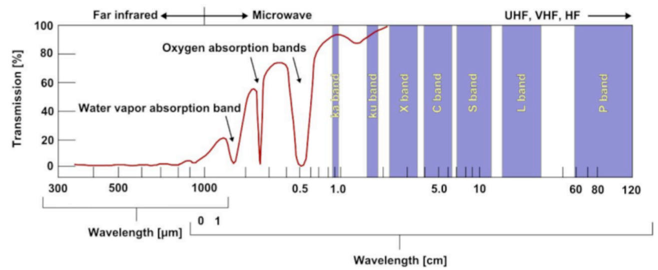
Remote Sensing in the Microwave

- As for other bands there are different types of remote sensing techniques
  - Passive systems
    - Typically with sensors in the region 1-200 GHZ
    - Based on the same principle of the thermal infrared
    - Very low emissivity and thus very large IFOV
    - Study of the snowfields, glaciers, wide-area precipitations...
  - Active systems
    - Non-Imaging: they provide one-dimensional measurements of a given “target”, like the distance or speed. For example altimeters, wind scatterometer etc.
    - Imaging: these instruments provide a two-dimensional reconstruction of the characteristics of an entire observed scene

Active Microwave Systems

- Main advantages
  - Possibility to acquire data on any time instant, including night time
  - The full control of the characteristics of the signal, including wavelength, polarization, incidence angle etc...
  - Possibility of using frequencies that allow the observation even in such situations where nothing can be observed in the visible band, for example in the case of clouds.
  - The possibility of measuring the time of flight, the phase and polarization difference between the signal sent and the return signal

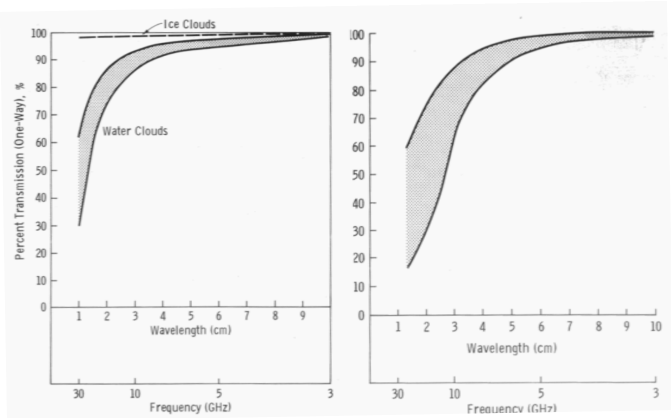
Microwave sub-bands



Frequency band	Wavelength (cm)	Frequency (GHz)
Ka	0.8-1.1	40 - 26.5
K	1.1-1.7	26.5 - 18
Ku	1.7-2.4	18 - 12.5
X	2.4-3.8	12.5 -8
C	3.8-7.5	8 - 4
S	7.5-15	4 - 2
L	15 -30	2 - 1
P	30 -100	1 - 0.3

Esempio di Trasmittanza

- Effetto delle nuvole e della pioggia



Clouds Rain

Microwave sub-bands

- We see that, for example, in the interval 1-10GHZ the trasmissivity is nearly 100%, practically independent from precipitations and clouds.
- This makes remote sensing possible in conditions which would be impossible in the visible . For some regions, like at the tropics, this makes a fundamental difference.
- When the frequency increases, attenuation becomes sensible
  - At 22 GHz there is an absorption band for the water vapor that reduces the transmissivity to around 85%
  - At about 60GHz the absorption band of the oxigen blocks almost completely the electromagnetic signal making remote sensing from higher atmosphere impossible.

Microwave sub-bands

- The interaction between wave and target is usually much different in the microwave than in the visible due the very different wavelength
- This makes remote sensing in the microwave much different from the one in the visible
- For example, a fundamental characteristic of different wavelengths in the microwave region is the different penetration on different materials.
- Short wavelengths only have a small penetration while long wavelengths can penetrate substantially deeper

RADAR (monostatic)

- RADAR: RAdio Detection And Ranging
- The main active sensor in the microwave region
- Working principle: an impulse is emitted by a source and is reflected by the target. The characteristics of the return signal allow one to study the properties of the target
- It is possible to render two-dimensional images as in the visible or IR regions, but the interpretation is far less intuitive for us because the interaction between wave and targets is so much different in the microwave than in the visible range.

RADAR

- Attention please: the word “Radar” is often associated with the notion of discovery radar or tracking radar, which is used to spot approaching objects, airplanes or ships and monitoring their trajectories
- Here we consider radars which are designed to study the properties of a target that is often well known to exist and whose position is known
- The physical principle used is the same, but this clearly changes the type of problem that we will need
- To solve

Plan Position Indicator (PPI)

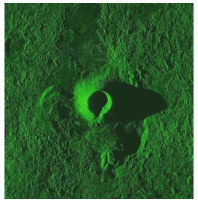


Immagine radar

RADAR

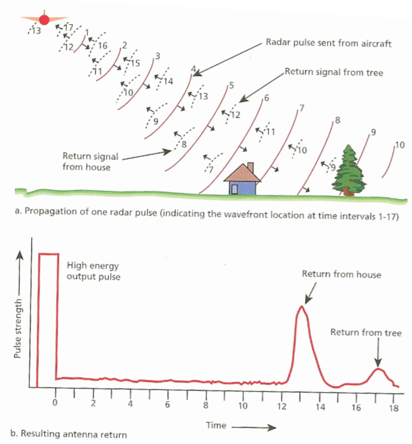
- The first experiments on the detection of boats by means of EM waves were done in the first years of ‘900
- In the 20s the first rudimentary pulsed radars for the detection of large objects are built
- During World War II the radars with the Plan Position Indicator (PPI, the typical circular monitor)
- In the 60s, the radar becomes a technology for the public domain
- 1978: SEASAT, the first radar satellite for civil applications
  - Radar altimeter
  - Microwave scatterometer for measuring the direction and speed of winds
  - Microwave Radiometer for measuring the temperature of the sea
  - It brings the first Synthetic Aperture Radar (SAR) in orbit

REAL APERTURE IMAGING RADARS

- We first see the basic working principle of a so called *Real Aperture Radar*, that is, a radar whose acquisition principles are based on the assumption that the platform is in a fixed position during elementary measurement operations
- Better said, the movement of the platform is only considered as a mean to move the sensor so that it can acquire data over different regions
- We will see later that, nowadays, the so called *Synthetic Aperture Radar* is used which exploits the motion of the platform to emulate an antenna larger than the physically available one. That is, the motion of the platform is used to improve the precision of each single acquisition

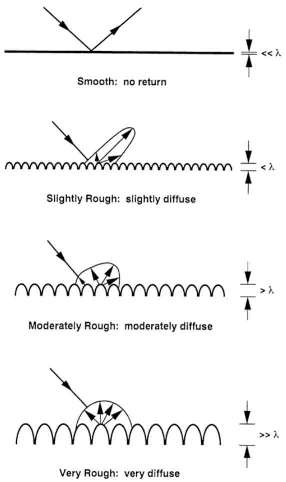
Basic principle

- The physical principle used is “similar” to that use with the LIDAR
- A series of pulses is sent to a target and the return signal is analyzed. By measuring the time of flight we obtain a measure of the distance of “the” target
- The most important difference is that
  - The beam has a much larger spot, which implies that different objects reflect each pulse
  - The intensity of the reflected pulses is used to create an image of the surface (imaging radar)



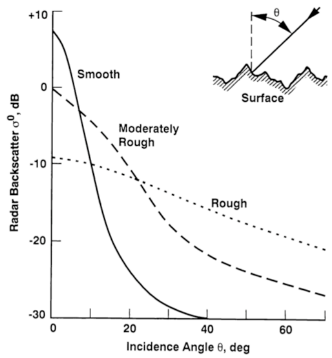
Surface Scattering

- As already seen, a surface exhibits a different behavior at different wavelengths
- This allows one to choose different frequencies depending on the properties that one wants to study of a give target
- The same thing can be said for the volumetric scattering



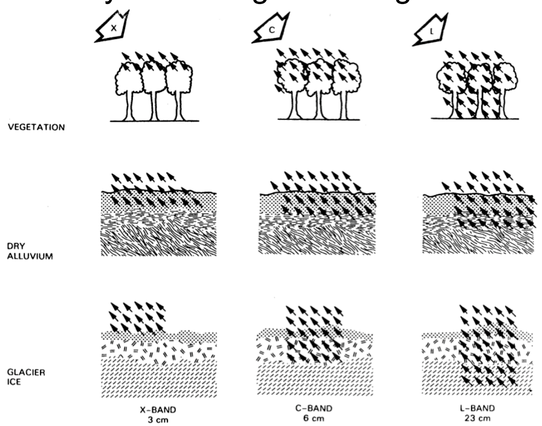
Surface Scattering

- Clearly, the backscattered power flux also depends on the angle between the incident wave and the surface
- Ad small incident angles, a smooth surface gives back more power than a rough surface
- At large angles, on the contrary, a rough surface gives more backscattered power than a smooth one



Application Example

- Different microwave bands can be used to study different layer of a vegetated region

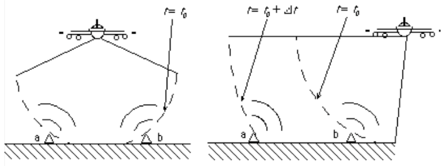


Polarization

- We will later see that the choice of polarization is as important as the choice of the frequency for certain applications
- Usually one considers both the polarization of the emitted wave and the polarization of the received return signal, measuring the four possible combinations HH, HV, VH and VV.
- These combinations allows one to detect different properties of some targets
  - Alignment of the target with respect to the radar (HH versus VV)
  - Scattering randomness (example: vegetation HV)
  - Reflection by corners (example: phase between HH and VV)
  - Etc...

Nadir-Looking and Side-Looking

- A fundamental difference between the optical imaging and the radar imaging technologies is the geometry of the acquisition
- The optical imaging instruments that we have seen are usually of the *nadir-looking* type, that is, they acquire the image in the vertical direction below the platform
- An imaging radar, instead, operates in *side-looking* mode, that is, it acquires the “image” from a lateral direction on only one side
- The reason for this is very simple: since it can only measure distances, it cannot distinguish the left hand side from the right hand side



SLAR: Side-Looking (Airborne) Radar

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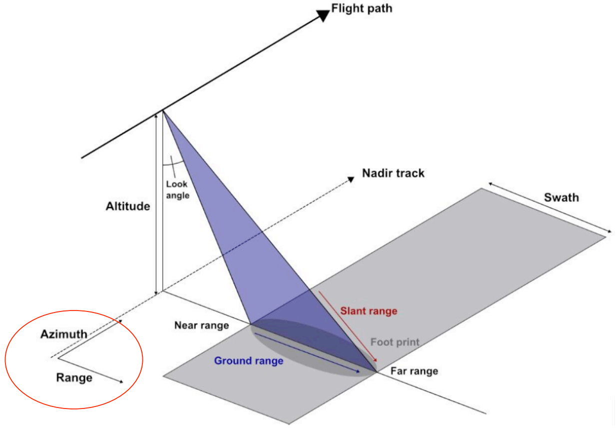
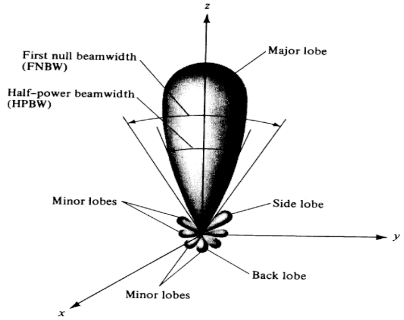


Directivity of the Antenna

- The used antenna is a highly non-isotropic antenna, with a flux that changes much depending on the direction
- The radiation diagram has one main lobe whose most important properties are the angular aperture in the azimut and in the elevation directions



Directivity of the Antenna

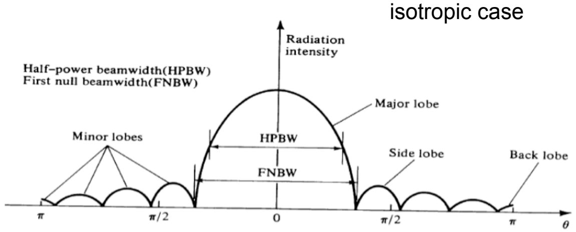
- The directionality is characterized by a gain G that allows one to express the power in one direction at a given distance R

Total power

Gain

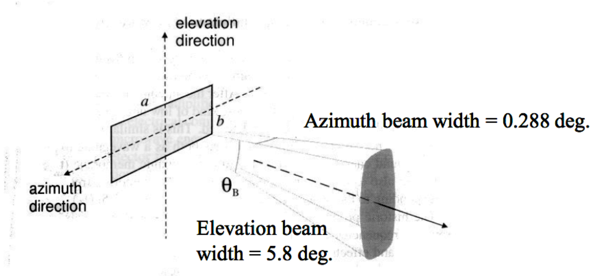
$$\Phi_T(R,\theta,\varphi) = \frac{P_T}{4\pi R^2} G(\theta,\varphi)$$

Power flux in the isotropic case



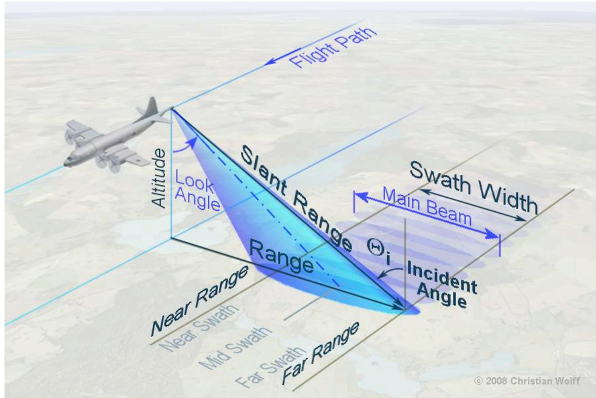
Directivity of the Antenna

- For a side-looking radar, the angular width of the lobe in the azimuthal direction is much lower than in the transverse direction (or in elevation)
- This is becasue in the azimuthal direction we would have the same problem as with the nadir-looking configuration



Acquisition geometry

- The geometrical configuration is thus as in the figure



Cross section

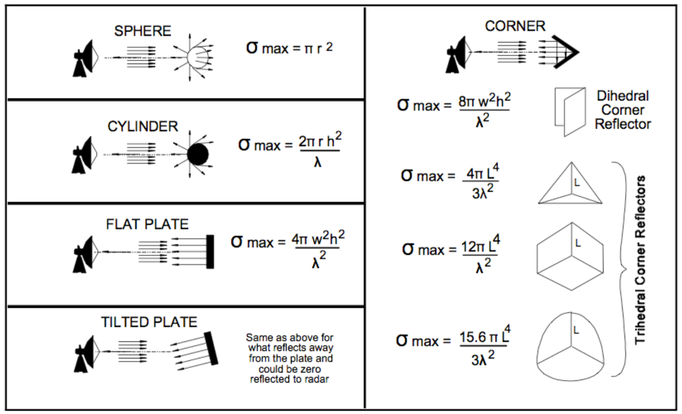
- The target will reflect in a different way depending on its size and shape
- This is usually expressed by means of a coefficient σ that allows to put in a relation the power that hits the target with the returned power

$$P_{\text{backscattered}} = \Phi_T \sigma$$

- It is possible to compute this coefficient for some simple shapes but it has to be determined experimentally for most objects of practical interest

Cross Section

- Examples



Received Power

- The power flux at the receiver is a fraction of the backscattered power inversely proportional to the fourth power of the distance

$$\Phi_R = \frac{P_{\text{backscattered}}}{4\pi R^2} = \frac{P_T G \sigma}{(4\pi)^2 R^4}$$

- The antenna will intercept only a fraction of the power depending on its effective area A_{eff}

$$P_R = \frac{P_T G \sigma A_{eff}}{(4\pi)^2 R^4}$$

The Radar Equation

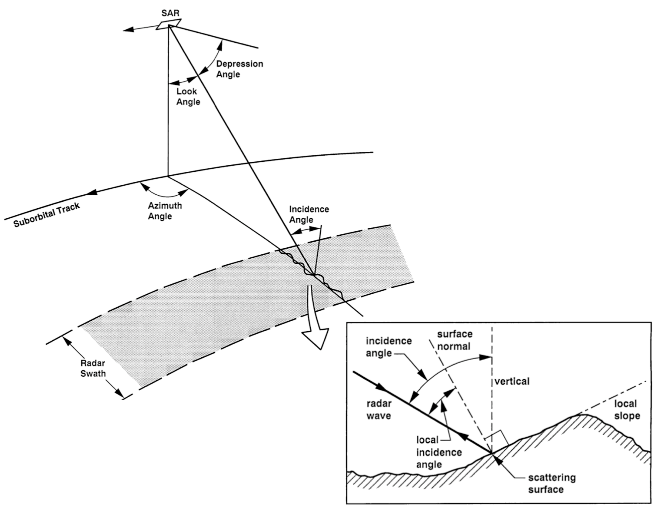
- Typically, the gain of the antenna in transmission can be related to effective area and one has

$$G = \frac{4\pi A_{eff}}{\lambda^2}$$

- Extracting the expression of the effective area from this equation, we can write the received power in terms of the transmitted power in the *radar equation* (in the monostatic case)

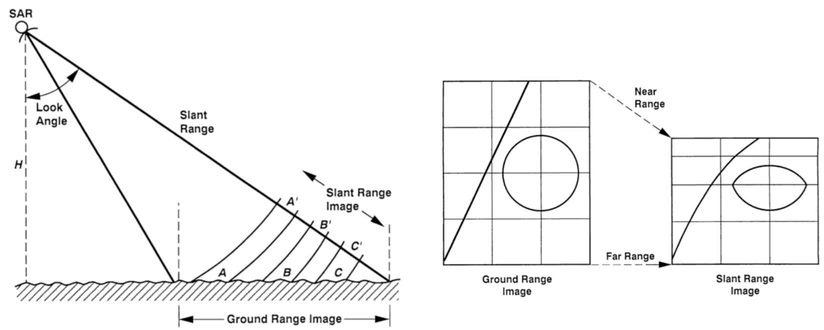
$$P_R = \frac{P_T G^2 \sigma \lambda^2}{(4\pi)^3 R^4}$$

Distortion: acquisition geometry

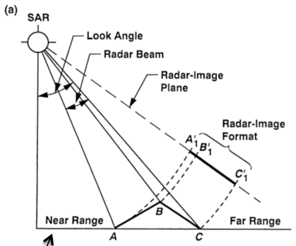


Distortion

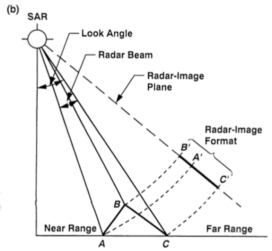
- Since the radar distinguishes the position of the objects by means of their distances, the ground image is mapped to a *range image* which is distorted near the nadir region



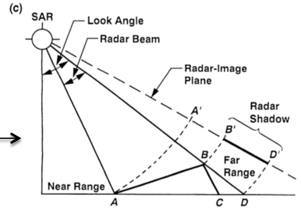
Types of Distortions



Foreshortening:
Region with the same physical slope and different range images. The region AB appears shorter and brigther



Layover:
Inversion in the position of A and B



Shadowing:
C is not seen due to the shadowing effect of AB

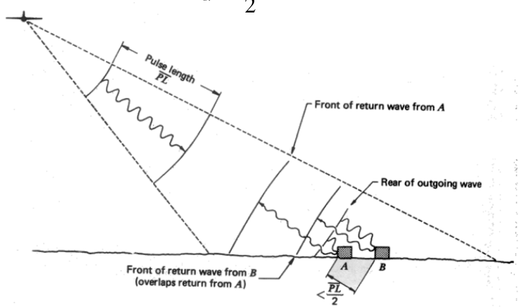
Resolution

- We must distinguish three types of resolutions
  - Slant range resolution: this is the resolution in the radial direction, that is the resolution in terms of the distance of the target from the antenna
  - Across-track, or ground range: the ground resolution in the transversal direction, that is, in the direction of the main extension of the wave beam
  - Azimuthal: the ground resolution in the direction of flight

Slant range resolution

- It is the minimal difference between the distances of two targets that the antenna can distinguish
- If a pulse has a duration of τ seconds, the resolution is

$$\rho_{sr} = \frac{\tau c}{2}$$

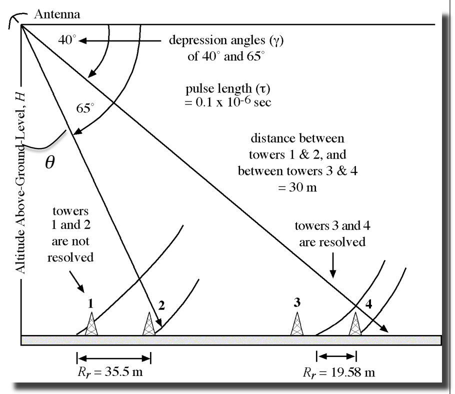


Ground range resolution

- Is directly related to the slant range resolution by means of the equation

$$\rho_{gr} = \frac{\rho_{sr}}{\sin\theta} = \frac{\tau c}{2\sin\theta}$$

- It depends on the angle and thus on the distance of the target from the vertical below the platform
- The resolution is thus lower (better!) in the far range than in the near range



Pulse "compression"

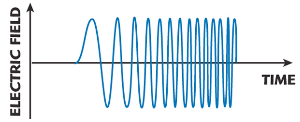
- In order to improve the ground range resolution it is necessary to shorten the pulses. This can also be seen as an increase of the bandwidth of the signal

$$\rho_{sr} = \frac{\tau c}{2} = \frac{c}{2B}$$

- The total energy of each pulse, however, would decrease when decreasing the pulse duration
- It would then be necessary to increase the power of the pulses while we decrease their duration, so that the total energy is kept fixed
- This can be impractical for different reasons (safety, high required voltages, costs...)

Pulse "compression"

- Solution: *chirped pulses*. The pulses are long in duration and have low power, but they are build with a "instantaneous frequency that increases in time"

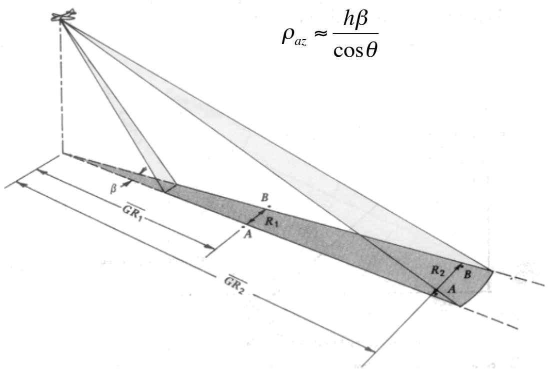


- This pulses allow the receiver to obtain almost the same resolution that would be obtained by shortening the pulses but with the advantage that the power is kept low
- This comes of course at the cost of a higher complexity of the receiver
- We do not go into the details but simply observe that
  - With this type of pulses, the used bandwidth is increased almost of the same amount that would be needed with short pulses
  - With proper operations, the receiver can distinguish close targets because they are distinguishable in the frequency domain

Azimuthal resolution

- The minimal detectable distance in the flight direction
- Two points can be distinguished in azimuth only if they are do not reflect the same pulse. Hence

$$\rho_{az} \approx \frac{h\beta}{\cos\theta}$$



Azimuthal resolution

- The azimuthal resolution is a fundamental parameter
- It does not depend in fact on the slant-range resolution and thus not even on the duration of the pulses (or their shape)
- It only depends on the width of the lobe in the flight direction and on the altitude (and whether we are in the near/far range)
- Usually, the width at of the lobe at -3dB can be approximated as

$$\beta \approx \frac{\lambda}{L}$$

where L is the length of the antenna. This implies

$$\rho_{az} \approx \frac{h\lambda}{L\cos\theta}$$

Azimuthal resolution

- Example:
  - Band X (λ=3.1cm)
  - L=10 meters
  - h=7Km
  - Θ=29º
  - Resulting azimuthal resolution... 24 meters.
- If we have with the same device h=700Km (satellite) we would obtain a resolution of nealy 2.5 Kilometers.
- This clarifies that real aperture radars cannot be used on satellite platforms if not with very poor resolutions

Azimuthal resolution

- How to increase the azimuthal resolution??
  - Use the real aperture radar only at low altitudes: obvious, in fact it is only used on airplanes... But what for satellites?
  - Use a longer antenna?
    Practically impossible, we would need huge antennas for even moderate resolutions
  - Use shorter wavelengths?
    We would face problems with the atmospheric absorption

Synthetic Aperture Radars

- In order to improve the azimuthal resolution a smart solution has been found which introduces a variation on the original idea of how the radar should operate
- Exploit the movement of the platform to emulate a longer antenna in the azimuthal direction.
- In practice, the radar emits a highly coherent wave and analyzes all the echoes from a given point while flying over, so as to simulate what would have been received by a longer antenna than the one physically available

Synthetic Aperture Radar (SAR)

- Principle developed in the ’50s
- If exploits the fact that the platform moves relatively fast
- It can be interpreted as a smart usage of the doppler effect, which acts in a different way depending on whether the target is approaching or had already been passed