FlyRADAR

Mars' subsurface exploration by low-frequency radar

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26/04/2023

Brief historical overview

- ✓ The foundation for radar systems in general was laid by Christian Hülsmeyer when he obtained the worldwide first patent in radar technology on April 30, 1904 (patent DE 165 546). Six years later Gotthelf Leimbach and Heinrich Löwy applied for a patent to use radar technology to locate buried objects with radar technology (patent DE 237 944). This system used surface antennas together with a continuous-wave radar

- ✓ In 1926, a pulse radar system was introduced and filed for a patent (DE 489 434) by Dr. Hülsenbeck. He noted that any dielectric variation would also produce reflections and that the technique had advantages over seismic methods.

- ✓ The first ground penetrating radar survey to be reported was the determination of the depth of a glacier in 1929 by Stern. Then the technology seemed to have lost interest until the late 1950's.

Brief historical overview

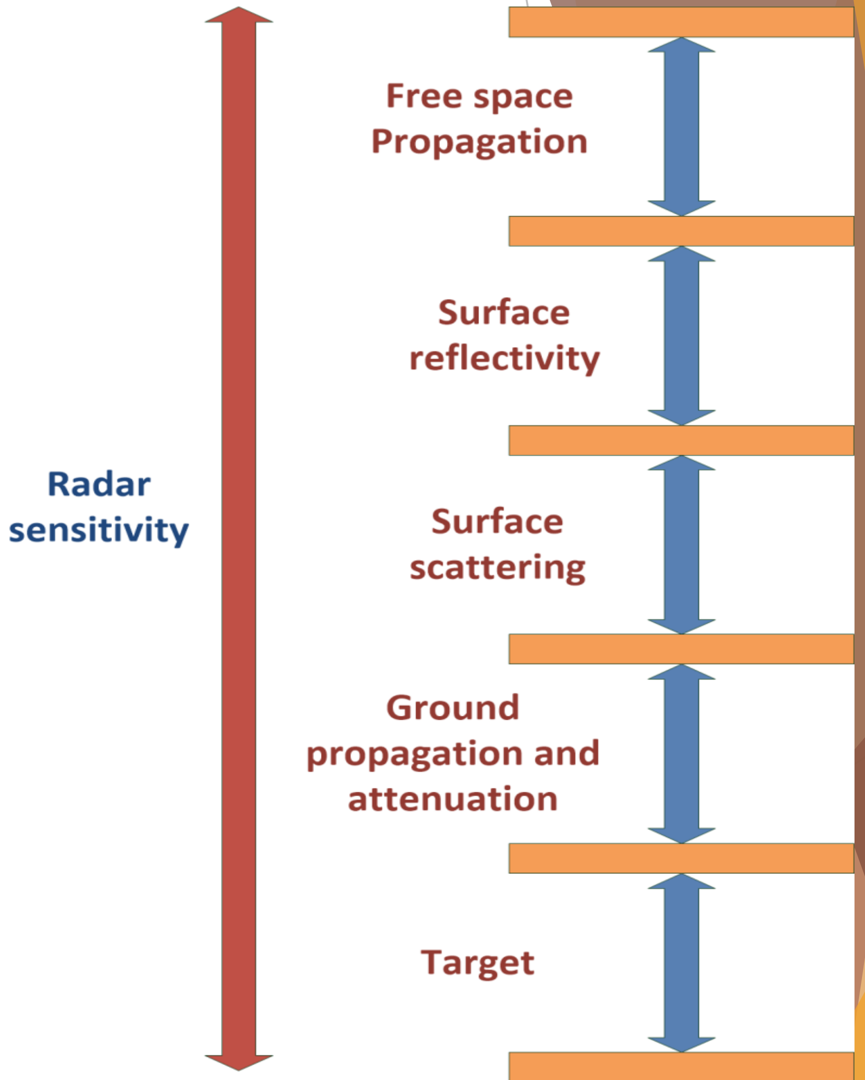
- ✓ From the beginning of the 1970's a lot of commercial applications using a GPR are mentioned in the literature, for example by Morey. The systems used in that time were exclusively impulse time domain systems. The applications were mainly found in the domain of civil engineering: location of voids, containers, tunnels and rocks, detection of cables and tubes, measuring the thickness of ice and coal layers, probing the profiles of lakes and rivers, etc.
- ✓ From then until today, the range of applications has been growing steadily. New applications as non-destructive testing, archaeology, roads and tunnel quality assessments, Earth remote sensing, Planetary exploration, etc. appeared.
- ✓ In 1988, D. J. Daniels, D. J. Gunton and H. F. Scott published a tutorial paper entitled "Introduction to subsurface radar", giving a good overview of the GPR technology at that time.
- ✓ In 1996, D. J. Daniels published his book on surface penetrating radar. Many engineers and researchers who are active in the domain consider the tutorial paper and the book to be reference works.
- ✓ Every two years, an International Conference on GPR is organised

The operating principle

- ✓ The Radar couples EM waves in the ground and samples the backscattered echoes
- ✓ The basic principle is that an EM wave will be backscattered on any electrical parameter contrast in the ground

$$\epsilon = permittivity$$
$$\mu = permeability$$
$$\sigma = conductivity$$

$$\varepsilon = \varepsilon_r \varepsilon_0 \qquad \varepsilon_0 = 8.85\text{x}10^{-12}\ [F/m]$$
$$\mu = \mu_r \mu_0 \qquad \mu_0 = 4\pi\text{x}10^{-7}\ [H/m]$$
$$\sigma \approx 10^7 \quad \text{per i metalli} \quad [S/m]$$



Terrain attenuation

- ✓ **Approximation of small losses it is usually accepted up to:**

$$\tan\delta < 1 \qquad \alpha \approx \frac{1}{2}\sigma\sqrt{\frac{\mu}{\varepsilon}}$$

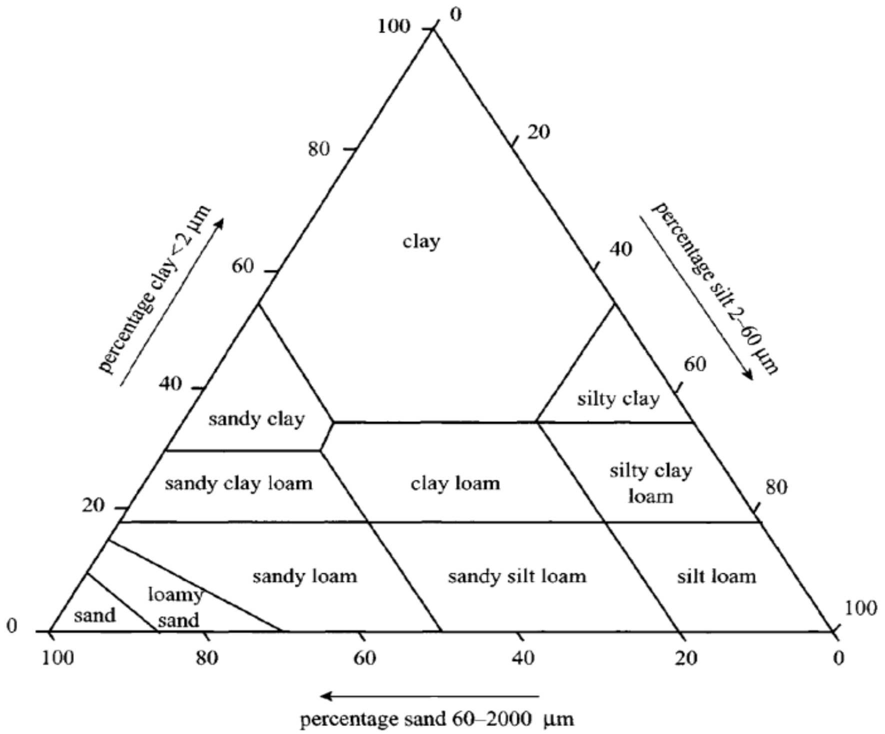
- ✓ **Within this approximation and for dry material it is reasonable to consider the loss tangent constant over the frequency range 10 MHz-10 GHz**

Conductivity and relative permittivity measured at a frequency of 100 MHz

Material	Conductivity, Sm^{-1}	Relative permeability
Air	0	1
Asphalt dry	$10^{-2}:10^{-1}$	2–4
Asphalt wet	$10^{-3}:10^{-1}$	6–12
Clay dry	$10^{-1}:10^{-0}$	2–6
Clay wet	$10^{-1}:10^{-0}$	5–40
Coal dry	$10^{-3}:10^{-2}$	3.5
Coal wet	$10^{-3}:10^{-1}$	8
Concrete dry	$10^{-3}:10^{-2}$	4–10
Concrete wet	$10^{-2}:10^{-1}$	10–20
Freshwater	$10^{-6}:10^{-2}$	81
Freshwater ice	$10^{-4}:10^{-3}$	4
Granite dry	$10^{-8}:10^{-6}$	5
Granite wet	$10^{-3}:10^{-2}$	7
Limestone dry	$10^{-8}:10^{-6}$	7
Limestone wet	$10^{-2}:10^{-1}$	8
Permafrost	$10^{-5}:10^{-2}$	4–8
Rock salt dry	$10^{-4}:10^{-2}$	4–7
Sand dry	$10^{-7}:10^{-3}$	2–6
Sand wet	$10^{-3}:10^{-2}$	10–30
Sandstone dry	$10^{-6}:10^{-5}$	2–5
Sandstone wet	$10^{-4}:10^{-2}$	5–10
Sea water	10^{2}	81
Sea-water ice	$10^{-2}:10^{-1}$	4–8
Shale dry	$10^{-3}:10^{-2}$	4–9
Shale saturated	$10^{-3}:10^{-1}$	9–16
Snow firm	$10^{-6}:10^{-5}$	6–12
Soil clay dry	$10^{-2}:10^{-1}$	4–10
Soil clay wet	$10^{-3}:10^{-0}$	10–30
Soil loamy dry	$10^{-4}:10^{-3}$	4–10
Soil loamy wet	$10^{-2}:10^{-1}$	10–30
Soil sandy dry	$10^{-4}:10^{-2}$	4–10
Soil sandy wet	$10^{-2}:10^{-1}$	10–30

Terrain attenuation

- ✓ **For lossy earth materials loss tangent is large at low frequencies, exhibits a minimum at around 100 MHz and increases to a maximum at several GHz, remaining constant thereafter**
- ✓ **Loss tangent is affected by both temperature and water content (the general effect of increasing the temperature is to reduce the frequency of the dielectric relaxation (*), while increasing the water content also increases the value of the loss factor while shifting its peak frequency down)**



Attenuation and relative dielectric constant of various materials measured at 100 MHz

Material	Attenuation, dB m^{-1}	Relative permittivity range
Air	0	1
Asphalt dry	2–15	2–4
Asphalt wet	2–20	6–12
Clay dry	10–50	2–6
Clay wet	20–100	5–40
Coal dry	1–10	3.5
Coal wet	2–20	8
Concrete dry	2–12	4–10
Concrete wet	10–25	10–20
Freshwater	0.01	81
Freshwater ice	0.1–2	4
Granite dry	0.5–3	5
Granite wet	2–5	7
Limestone dry	0.5–10	7
Limestone wet	1–20	8
Permafrost	0.1–5	4–8
Rock salt dry	0.01–1	4–7
Sand dry	0.01–1	2–6
Sand wet	0.5–5	10–30
Sandstone dry	2–10	2–5
Sandstone wet	4–20	5–10
Sea water	100	81
Sea-water ice	1–30	4–8
Shale dry	1–10	4–9
Shale saturated	5–30	9–16
Snow firm	0.1–2	6–12
Soil clay dry	0.3–3	4–10
Soil clay wet	5–50	10–30
Soil loamy dry	0.5–3	4–10
Soil loamy wet	1–6	10–30
Soil sandy dry	0.1–2	4–10
Soil sandy wet	1–5	10–30

(*) The readjustment of molecules in response to an electric field

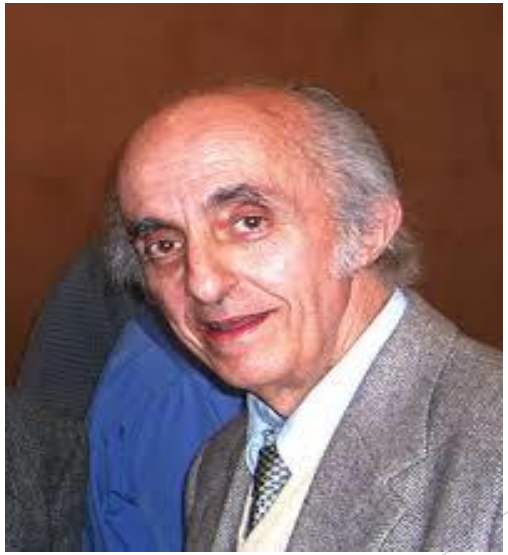
Mars exploration

✓ Two radar instruments are currently operative, on-board of two satellite missions

✓ This technology has been tested first outside the Earth: a unique case in the remote sensing world

MARSIS

- ✓ The Mars Advanced Radar for Subsurface and Ionospheric Sounding (MARSIS) instrument flown on the European space agency (ESA) Mars Express spacecraft.
- ✓ It is the first space-borne sounding radar since the Apollo 17 Lunar Sounder in 1972
- ✓ Prof. G. Picardi conceived this instruments and first he envisaged its potentialities for Mars exploration. It followed the design and development of the radar and he participated to data processing and analysis until his death in 2015.

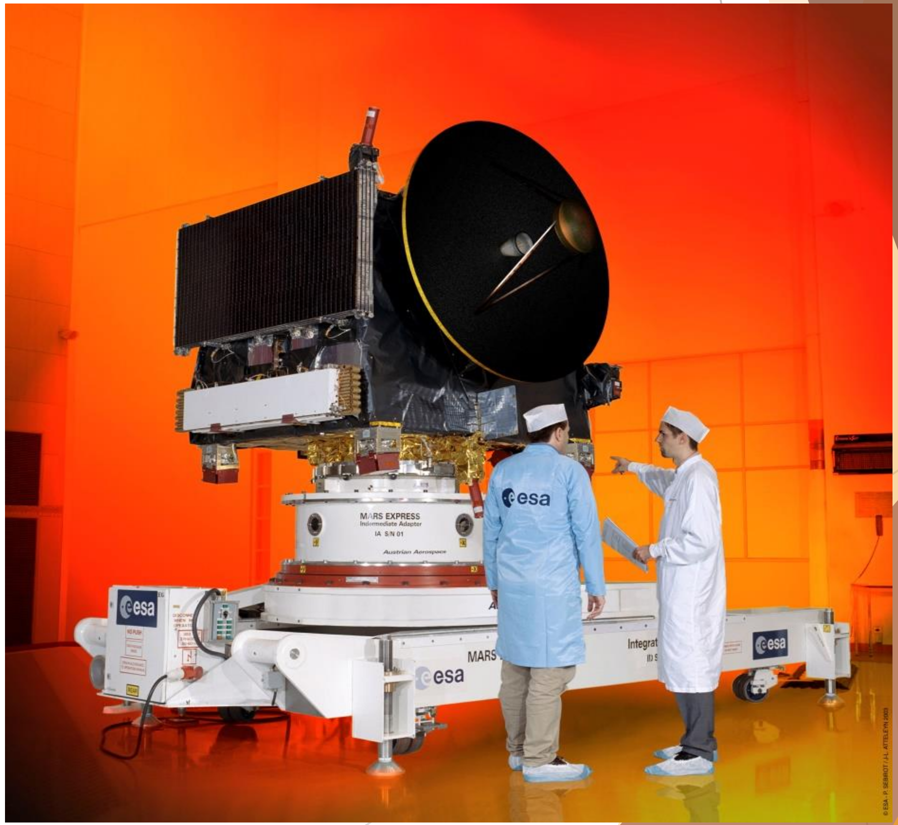


MARSIS

- ✓ The radar MARSIS is a co-operative project funded by NASA and ASI whose technical leadership was co-shared between actual Thales Alenia Space Italia (TASI) and JPL.

- ✓ TASI was in charge of the overall Mars Express spacecraft Integration and Testing

- ✓ TASI was also responsible for the design of the Digital Control and Processing Subsystem (DES) of the radar and the coordination of AIV/AIT activities of the overall instrument that has been integrated in Rome plant



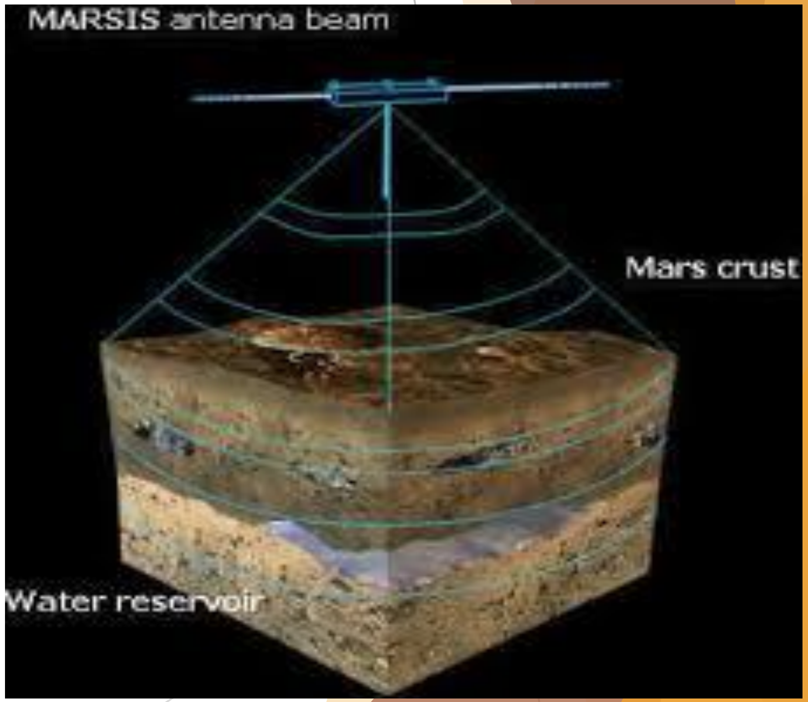
MARSIS

- ✓ The primary science objective of MARSIS is to map the distribution of solid and liquid water in the upper portions of the Mars' crust.

- ✓ Three secondary science objectives are subsurface geologic probing, surface characterization, and ionospheric sounding.

- ✓ The MARSIS instrument is a low-frequency, nadir-looking, pulse-limited radar sounder that uses synthetic aperture techniques

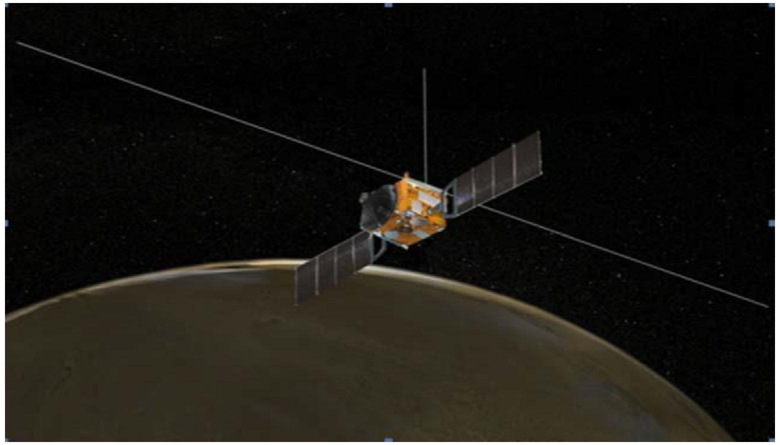
- ✓ The Mars Express spacecraft is in a highly elliptical 7 h orbit around Mars. Each MARSIS subsurface sounding pass has a duration of 26–30 min
- ✓ During these operations, spacecraft power and data resources are shared with five other instruments
- ✓ The MARSIS subsurface sounding modes can be effectively operated at altitudes lower than 900km



MARSIS

- ✓ The MARSIS transmitter generates a swept frequency high-power RF pulse that is delivered to a 40m dipole antenna for radiation
- ✓ This radiated energy is reflected from the Martian surface and subsurface back to the radar

- ✓ Data processing is performed on board in the MARSIS instrument. It utilizes the technique of Doppler beam sharpening (DBS) in order to enhance the ratio of subsurface echoes to surface clutter



MARSIS subsurface sounder parameters

Parameter	Description
Subsurface sounding altitude range	250–900 km
Dipole antenna length	40 m tip to tip
Monopole antenna length	7 m
Subsurface sounder frequency range	1.3–5.5 MHz (4 Bands)
Peak radiated power	1.5–5 W
Subsurface sounder pulse repetition rate	127 Hz
Subsurface sounder transmit pulse length	250 μs
Subsurface sounder wavelength	60–160 m
Bandwidth per band	1 MHz
Sounder free space depth resolution	150 m
Sounder dynamic range	40–50 dB
Nominal depth window	15 km
Number of processed channels	2 or 4
Number of simultaneous frequencies	1 or 2
Data quantization	8 bits per sample
Data quantization rate	2.8 megasamples per second
Data window duration	350 μs
Data rate output	18–75 Kbps
Data volume	285 Mbit per day
Dc operation power	60 W
Total mass	20 kg

MARSIS

- ✓ The subsurface sounder operates over a 1.3–to 5.5MHz range over four frequency bands of 1MHz bandwidth each. This frequency range corresponds to a wavelength range of 230–55 m.
- ✓ The subsurface sounder has two separate channels. The first channel is connected to the dipole antenna and contains the transmitter and a receiver. The second channel is connected to the monopole antenna and can only receive.

Frequency Bands	1.3-2.3 MHz, 2.5-3.5 MHz, 3.5-4.5 MHz, 4.5-5.5 MHz
Vertical Resolution (e_r = 5)	~70 m (1 MHz Bandwidth) [150 m free space]
Penetration Depth	from ~0.5 km to ~5 km
Horizontal Resolution	5-9 km x 15-30 km (along-track x cross-track)

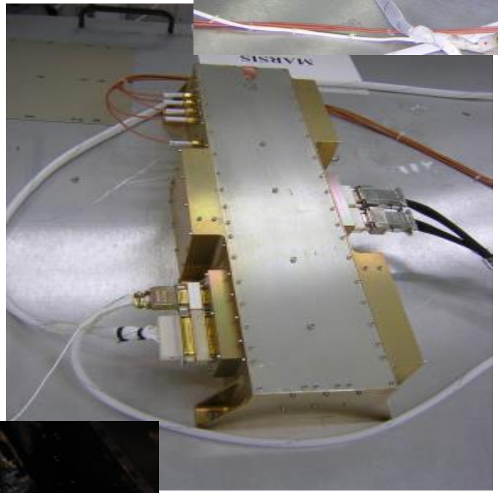
MARSIS

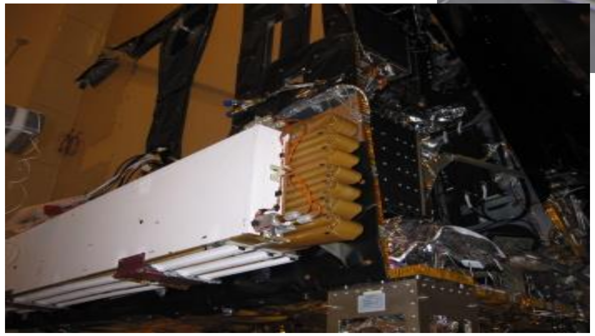
- ✓ **MARSIS instrument is composed by three different subsystems:**

DES: Digital Electronics Subsystem
Command & Control and Interface with S/C
Timing Generation

TX Signal Generation
Real Time Processing of Received Echoes
RFS: Radio Frequency Subsystem
Amplification of TX Signal
Impedance matching between Transmitter and ANT
Reception and AD Conversion of radar echoes

Antennas Subsystem
Primary Dipole Antenna (40m)
Secondary Monopole antenna (7m)

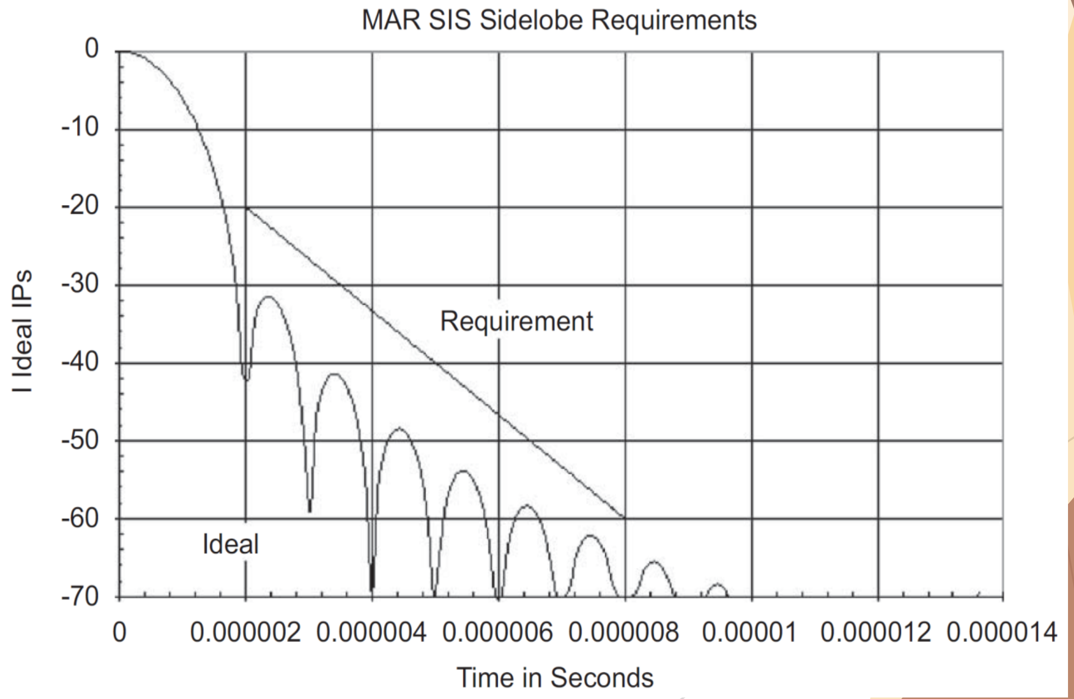




MARSIS

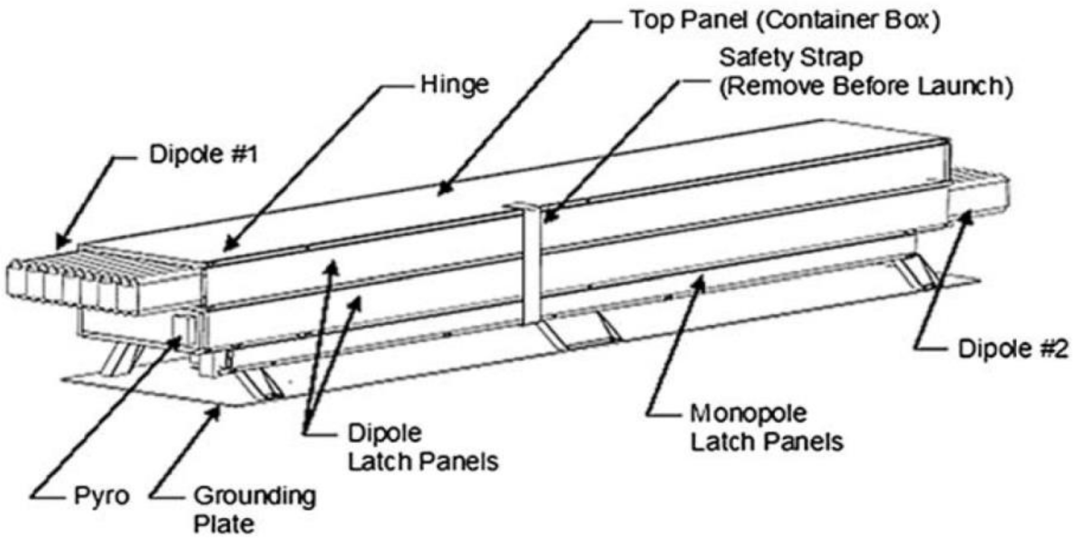
- ✓ In order to acquire data with a sufficient signal-to-noise ratio, MARSIS employs a chirp signal for transmission in the subsurface sounding modes
- ✓ This chirp is a 1MHz bandwidth frequency-swept signal of 250 ms duration
- ✓ During on-board or ground data processing, the return signal is range compressed, resulting in an increase in the signal-to-noise ratio of about 24 dB.

- ✓ During the design of the MARSIS electronics, the control of pulse compression sidelobes was an overriding issue, because the expected return of the first specular signal was calculated to be very strong compared to the calculated subsurface reflections



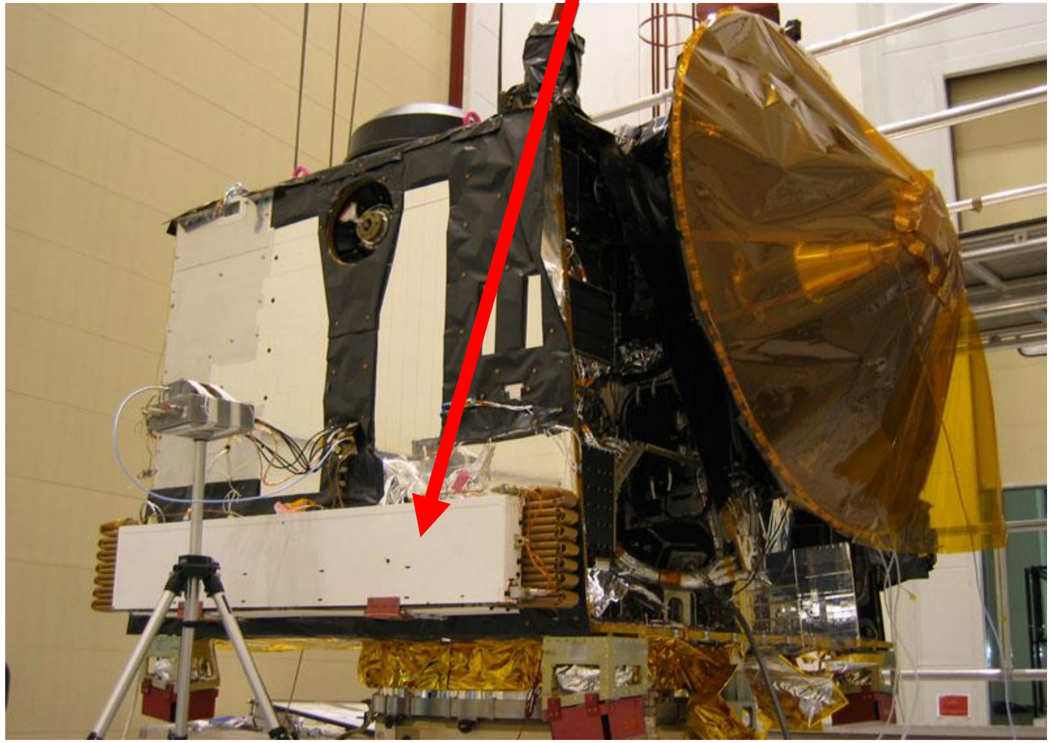
MARSIS

- ✓ The MARSIS antenna subsystem consists of a 40m long dipole and a 7m long monopole
- ✓ The antenna structure is essentially a bridge of two parallel wires running the length of a support tube, which is made of fiberglass and Kevlar layers impregnated with resin
- ✓ The antenna elements are made of foldable composite tubes that utilize a new technology developed by the Northrup Grumman called foldable flattenable tube (FFT)

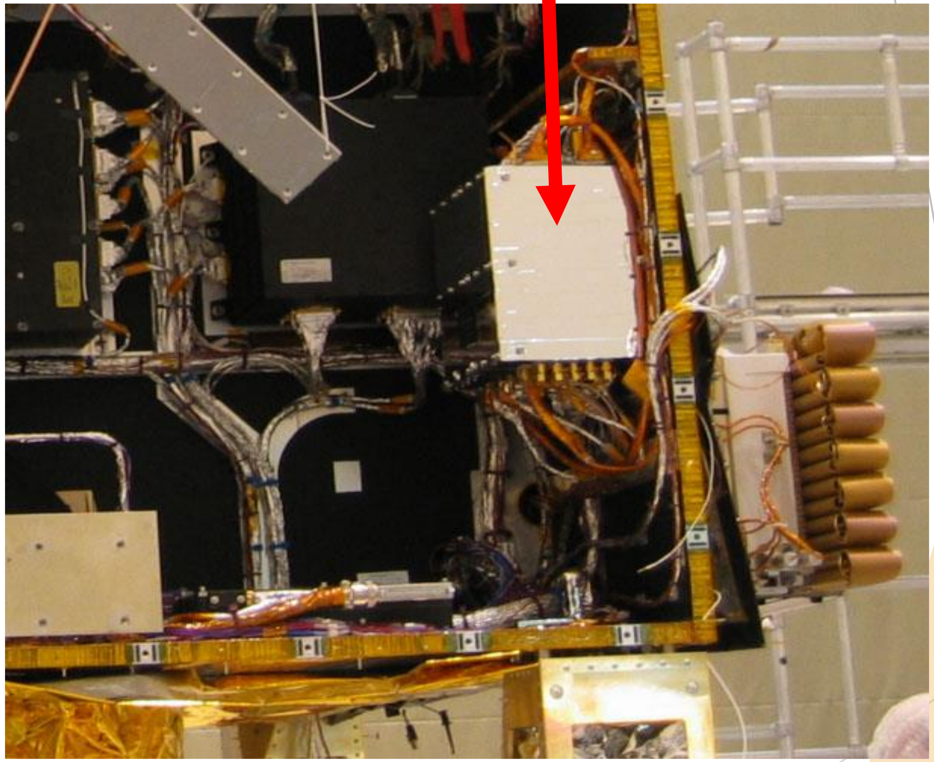


MARSIS

Stowed Antenna

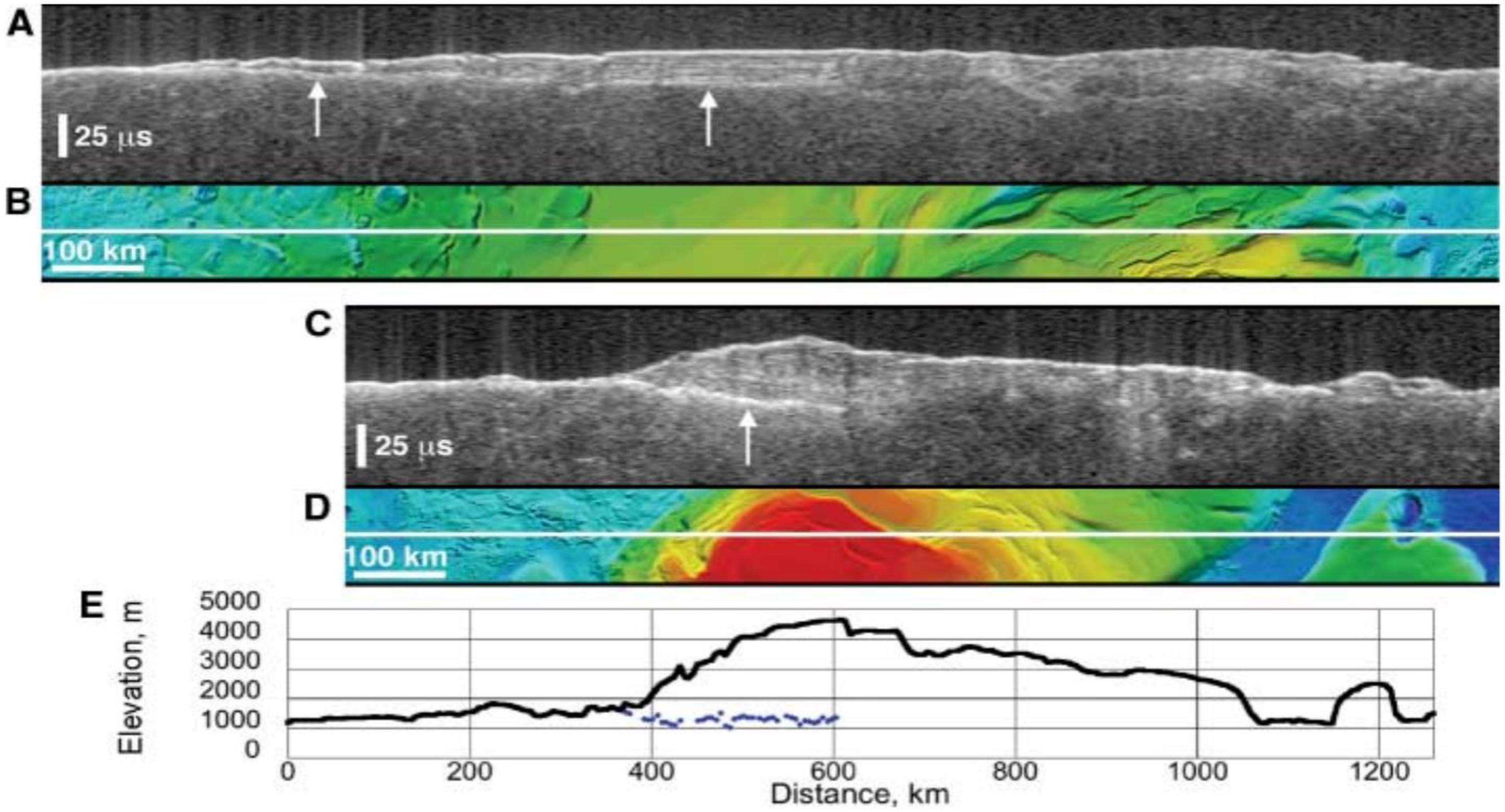


DES



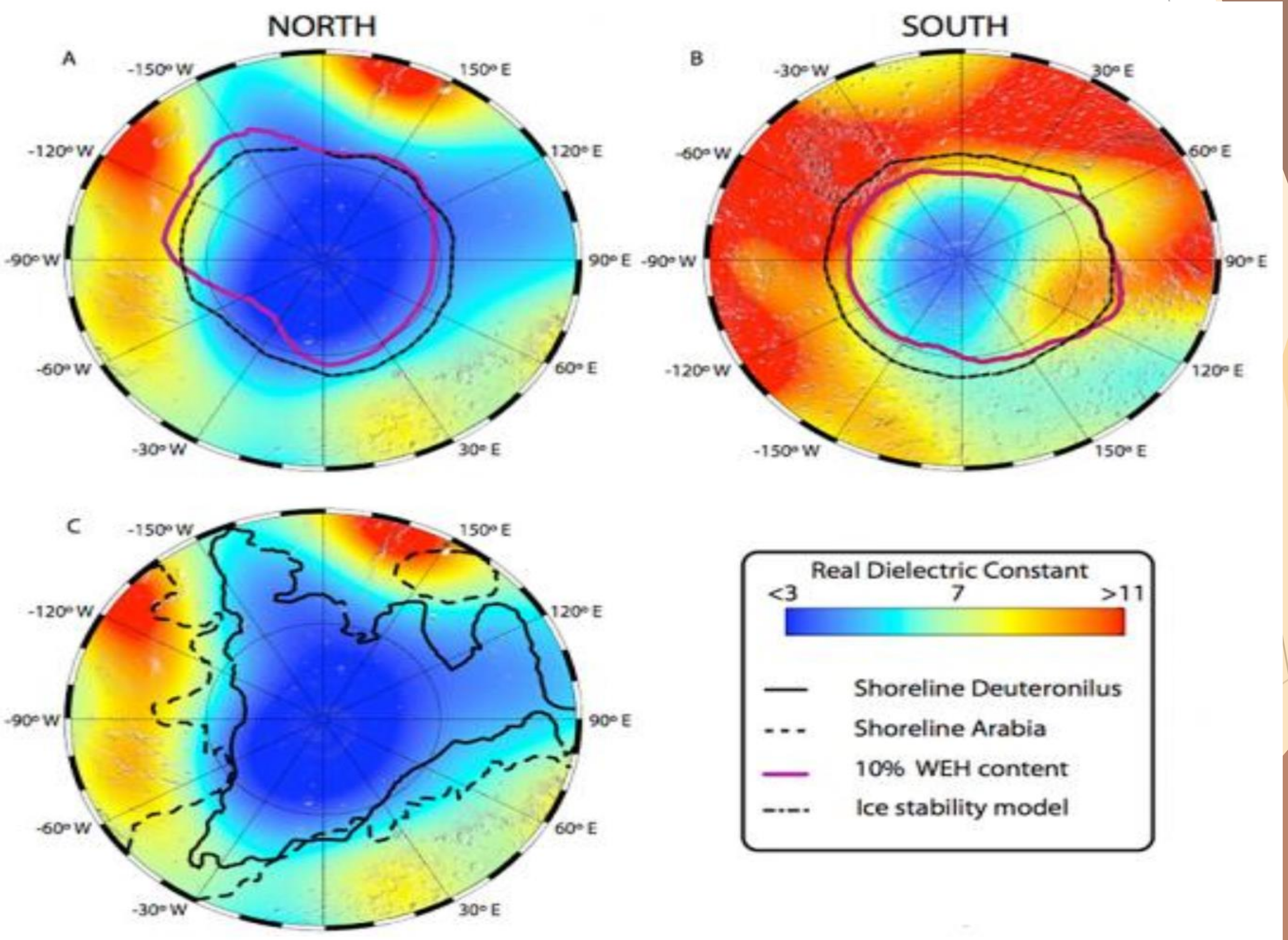
MARSIS

- ✓ **Data from the subsurface of Mars in the water-ice-rich layered deposits that surround the south pole of the planet**



MARSIS

- ✓ Map of a property that MARSIS' returned radio signals reveal about the material that Mars' ground is made of.
- ✓ Blue areas denote low dielectric constants and red areas denote high dielectric constant.



SHARAD

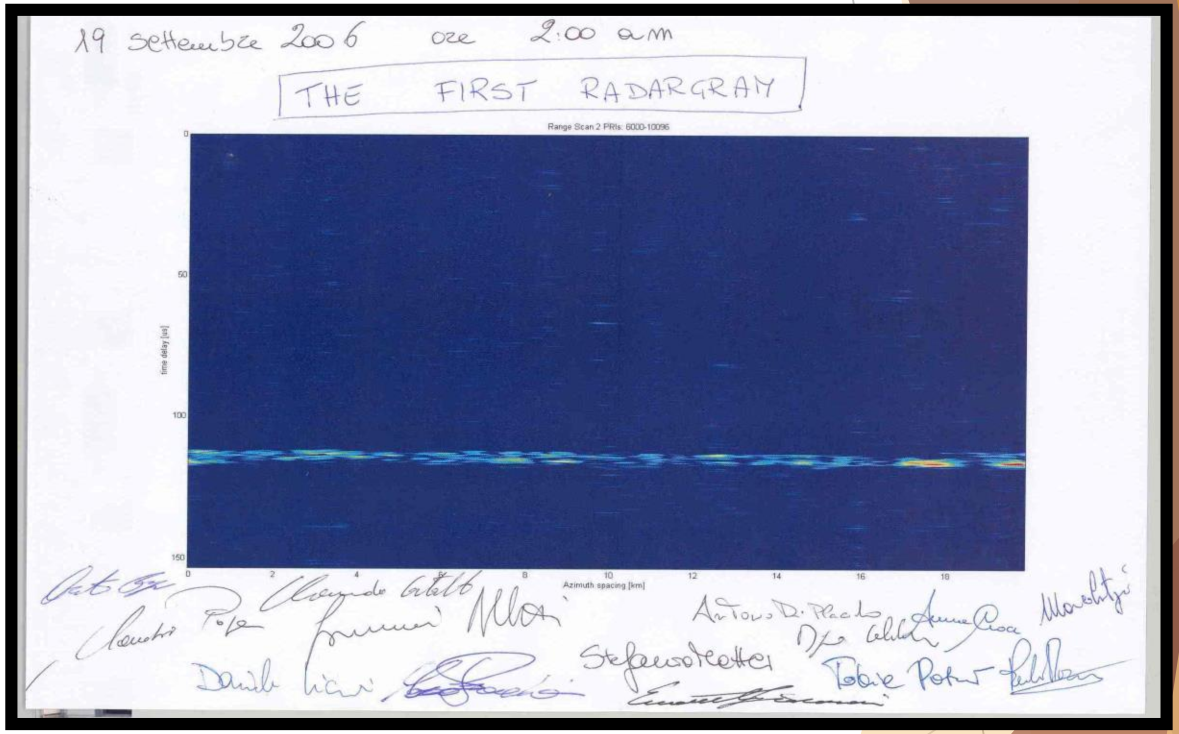
- ✓ **SHARAD (SHAllow RADar) is a nadir looking synthetic aperture subsurface sounding radar provided by the Agenzia Spaziale Italiana (ASI) on-board the NASA Mars Reconnaissance Orbiter (MRO)**
- ✓ **Instruments has been developed by the actual Thales Alenia Space Italia**

Science objectives

- ✓ **Map subsurface dielectric discontinuities, interpreting them in terms of occurrence and distribution of various materials, including solid rock, regolith, water and ice**
  - Detect liquid water and profile of ice layers within the first few hundreds meters of the Martian subsurface
  - Map the thickness, extent and continuity of the layers within the polar deposits
  - Map the thickness, extent and continuity of sedimentary layers
  - Map the distribution of shallow buried channels
  - Identify regions on Mars for follow-up surface-based water/ice exploration.

SHARAD

- ✓ MRO was launched from Cape Canaveral Air Force Station on August 12, 2005, and reached Mars orbit on March 10, 2006
- ✓ On September, 2006, SHARAD antenna was successfully deployed, and calibration/commissioning phase was executed
- ✓ The radar entered its operational life on November 2006



SHARAD

Main system parameters

Centre Frequency:	20 MHz
Pulse Bandwidth:	10 MHz
Radiated Peak Power:	10 W
Pulse Length:	85 us
Antenna Efficiency:	> 10%
Pulse Repetition Frequency:	700 Hz, 670Hz, 775 Hz (350, 335, 387.6 Hz) alternate PRF added to cope with orbital extremes during extended phase (including topography margin)
Receive window:	135 us
Receiver gain:	80 dB
A/D Resolution:	8 bits
Downloaded sample bits	8 (default), 6, 4
A/D frequency:	26.67 MHz
Maximum Data Rate:	20.16Mbit/s (@ 700 Hz, no pre-summing)
On-board pre-summing range:	1 to 32 samples

SHARAD

Requirements/performance

Topography and orbit	SHARAD shall be able to operate in all MRO orbit conditions	• The instrument shall be able to operate over an orbit altitude range of 230-407 Km
Range resolution	15 m (free space, w/o weighting)	• The radar system shall provides a theoretical range resolution (at -4 dB) of 15 ± 0.3 meters in free space propagation. • The radar system shall provide a theoretical range resolution (at -4 dB) of 24.8 ± 0.5 meters in free space propagation assuming Hanning weigthing. • Maximum acceptable MLB shall be 1 meter (after calibration).
Horizontal resolution	300-1000 m along-track, 1500-8000 across-track	• Along Track Resolution better than 1000 meters. Worst case: in presence of specular surfaces, the synthetic aperture length will be limited by the Fresnel zone diameter: RAZ ~ 750 m. • Cross Track Resolution better than 7000 m after on ground processing. • Pulse-limited resolution : ~ 5.5 ÷ 6.2 Km .
Penetration depth	100's of meters (depending on subsurface structure and composition) up to 1 Km	• Affects SNR requirement
Carrier frequency and bandwidth	20 MHz 10 MHz	• The instrument shall operate within the frequency interval (-3 dB values) 15 – 25 MHz.±2%
Dynamic	50 dB	

SHARAD

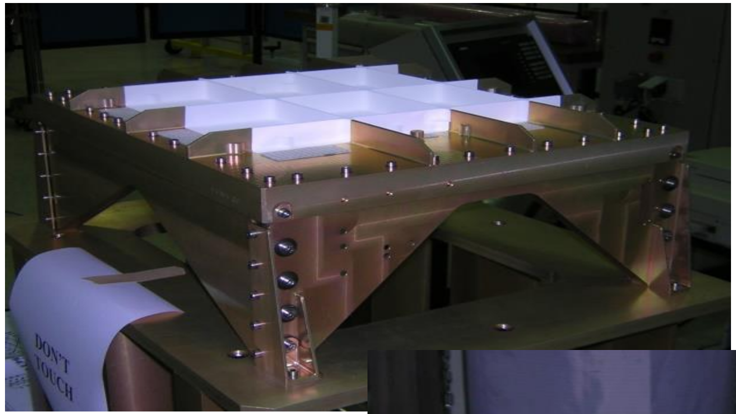
- ✓ **SHARAD is composed by two assemblies**
  1. SHARAD Electronics Box (SEB)
  2. SHARAD Antenna

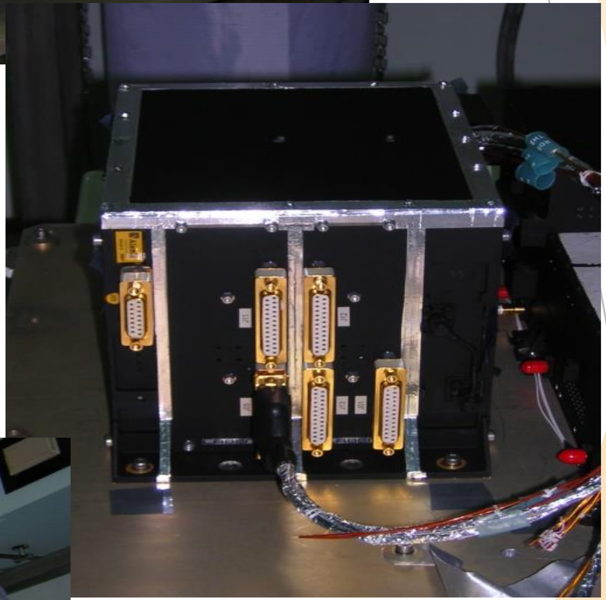
SEB is composed by two sub-assemblies

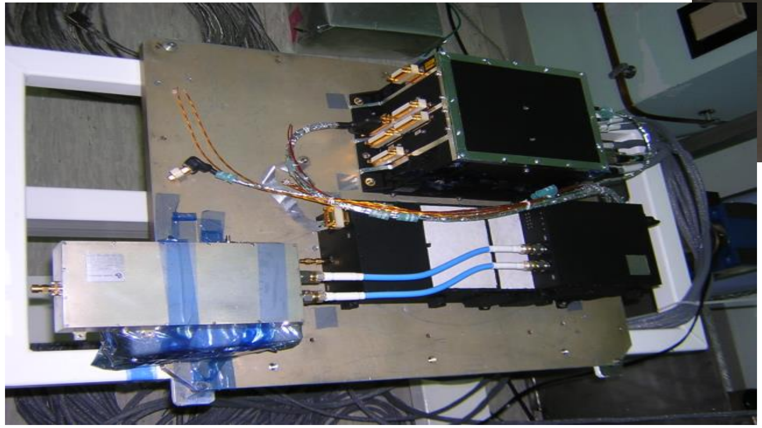
1. Transmitter and Front End (TFE)
2. Receiver and Digital section (RDS)

RDS is composed by two units

1. Receiver (RX)
2. Digital Electronics Section(DES)
   - 2.1 Power Supply Board
   - 2.2 C&C Board
   - 2.3 Timing Board
   - 2.4 Slave Board
   - 2.5 Chirp Generator







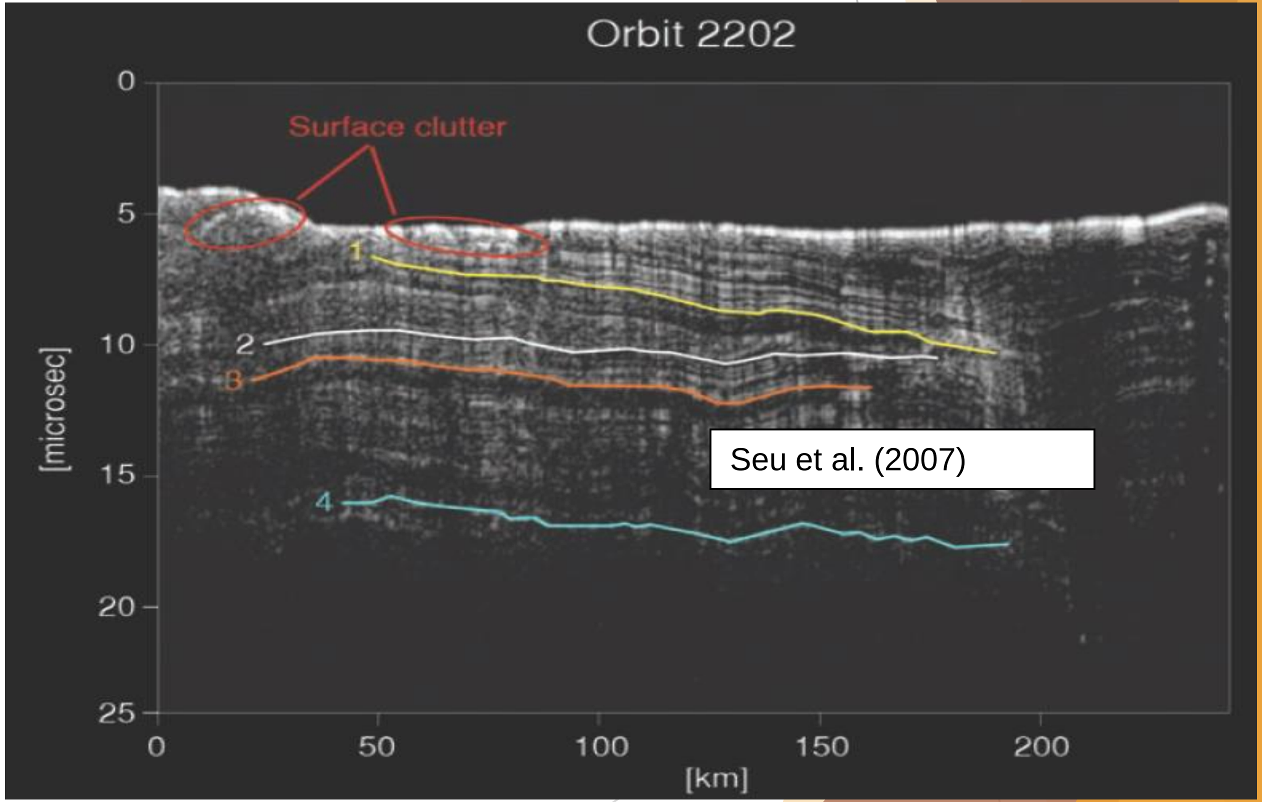
SHARAD

SHARAD

Effects of climate change in the South Polar Layered Deposits

- ✓ **Early observations of the SPLD revealed that layers undergo cycles of erosion and subsequent deposition, probably tied to variations in the tilt of the Martian axis of rotation**

Some results…

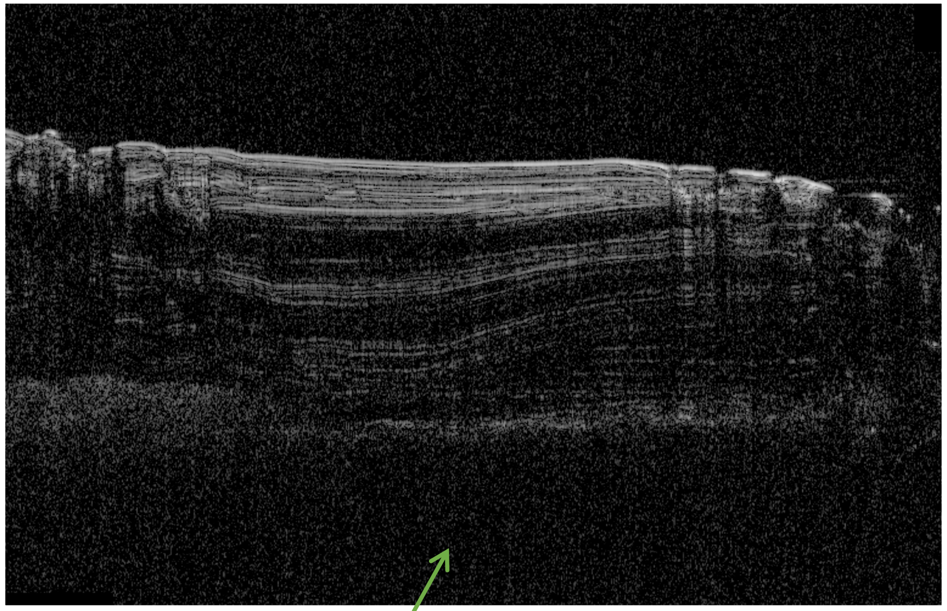


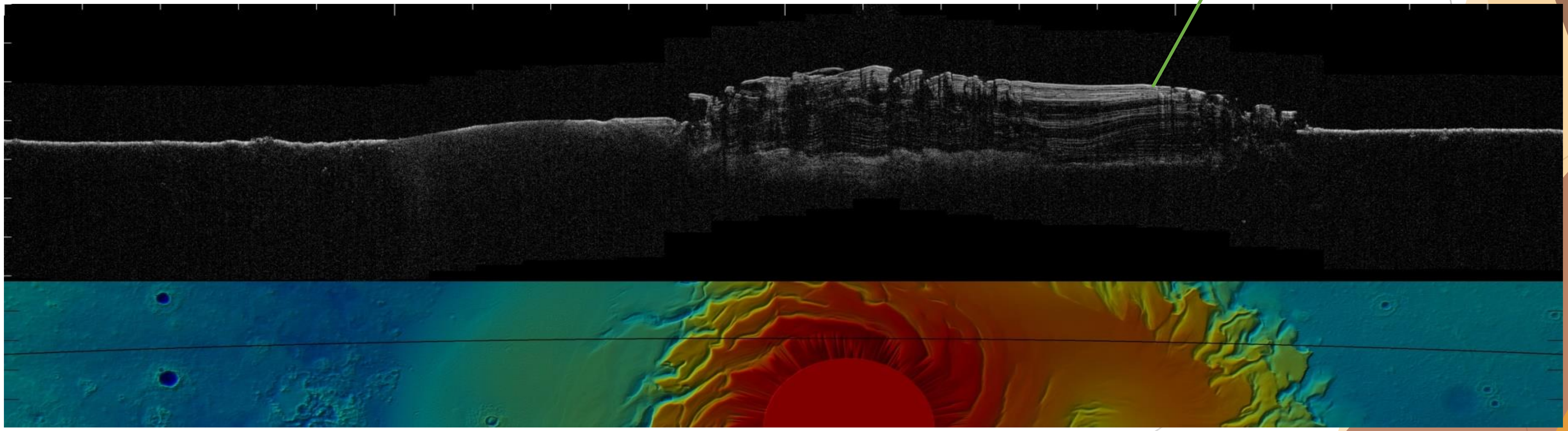
Seu et al. (2007)

SHARAD

Some results…

- ✓ **North Pole Layered Deposits (NPLD)**

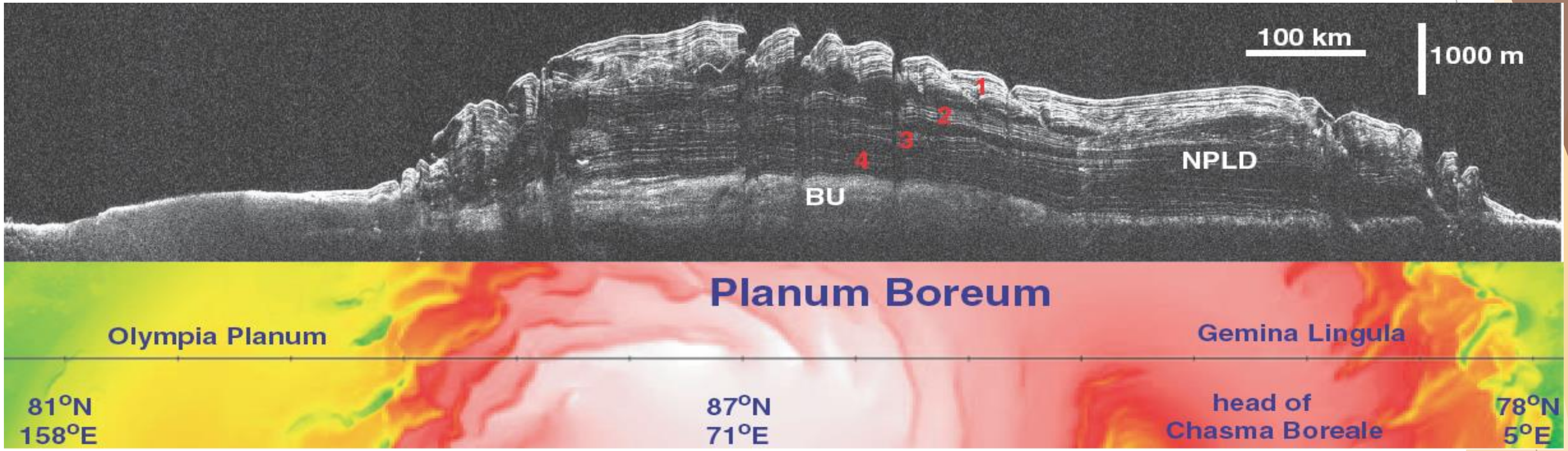




SHARAD

Some results…

<u>The Martian crust is thicker than previously though, the interior is colder</u>

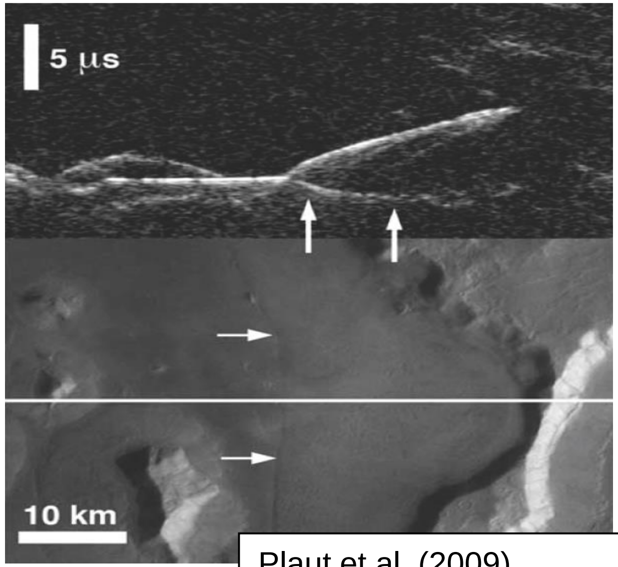


- ✓ **The Martian crust does not flex under the weight of the North Polar Layered Deposits, implying a thick litosphere**
- ✓ **The temperature of the subsurface does not reach the melting point of ice as close to the surface as previously thought**

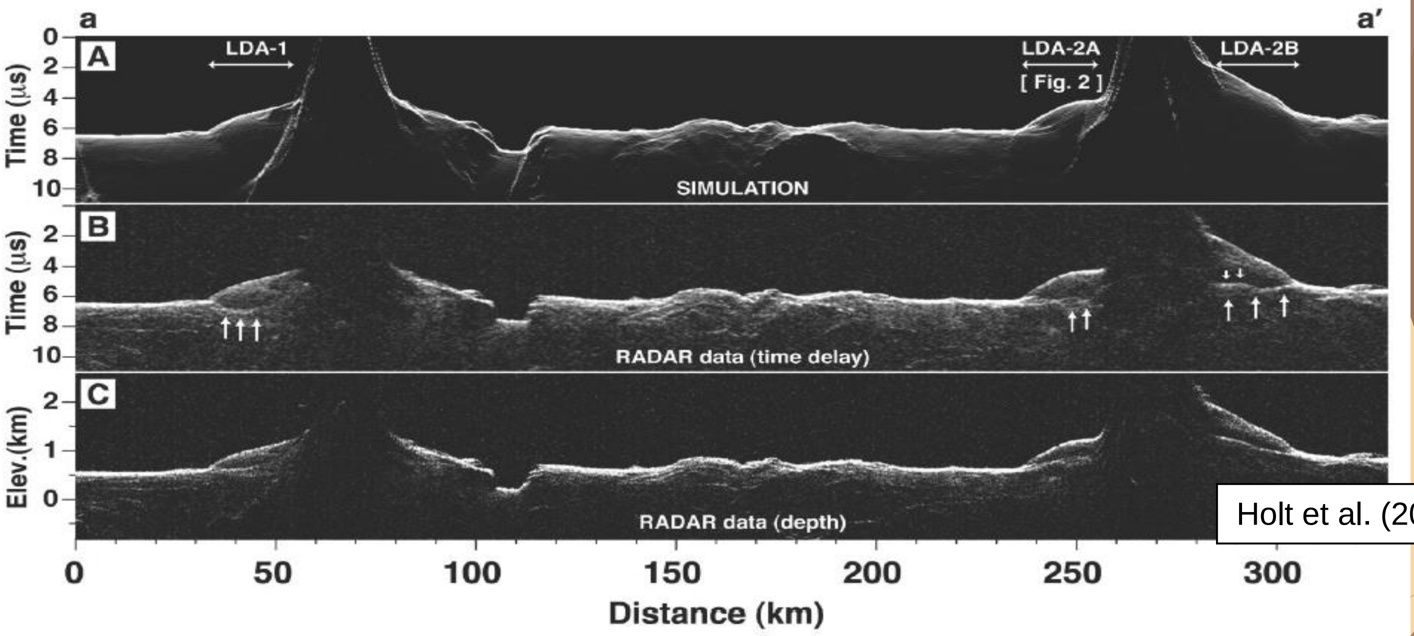
SHARAD

Some results…

Glaciers surviving from a previous ice age in the mid latitudes of Mars



Plaut et al. (2009)



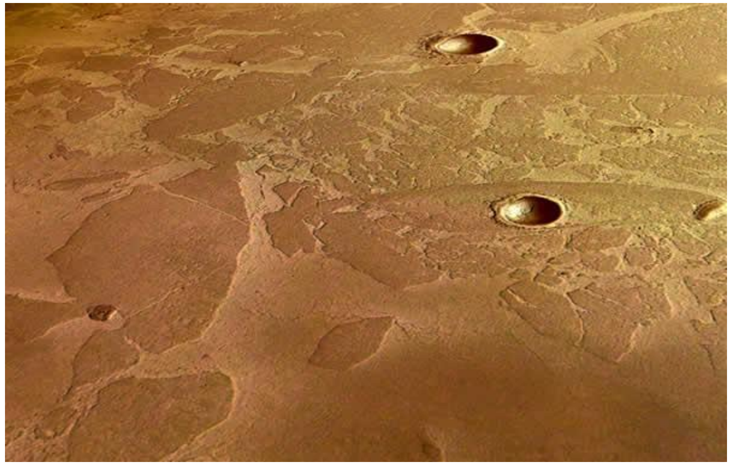
Holt et al. (2008)

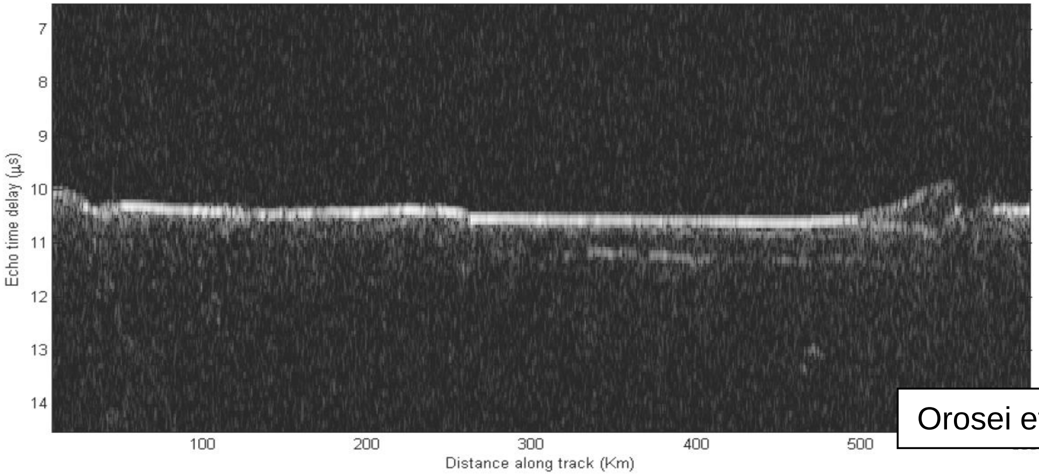
- ✓ **SHARAD observations revealed that landforms suspected of being glaciers, but covered by dust, are in fact made of ice**
- ✓ **These can be found both in the northern and southern hemispheres, at latitudes around 40°, and constitute perhaps the largest ice reservoir outside the polar caps**

SHARAD

Some results…

A frozen sea near the equator of Mars?





Orosei et al. (2010)

- ✓ **A surface feature resembling polar pack ice on Earth was found close to the equator of Mars**
- ✓ **SHARAD sounded the area to determine if there is really a sea frozen in place**
- ✓ **Dielectric properties of the surface material are not those of water ice, but neither those of lava flows: the puzzle is still to be solved**

Resolution

- ✓ Vertical resolution depends on trasmitted bandwidth $$\rho_R = \frac{c}{2B\sqrt{\varepsilon_r}}$$

- ✓ For pulsed unmodulated radar, high resolution requires very short pulses. This means high peak power at the expenses of transmitted averaged power

$$\rho_R \approx \frac{c}{2}\tau$$

- ✓ Chirp is a frequency modulated (linearly) signal, that allow to transmit large bandwidth with long pulses

$$ch(t) = \exp\left(j\pi \frac{B}{\tau} t^2\right) \qquad t = \left[-\frac{\tau}{2}, \frac{\tau}{2}\right]$$

Resolution

✓ Horizontal resolution depends on antenna beamwidth and distance from surface (H)

$$\rho_H \approx H\theta_{3dB}$$

✓ Doppler effect can be used for increasing horizontal resolution at least in the along-track direction

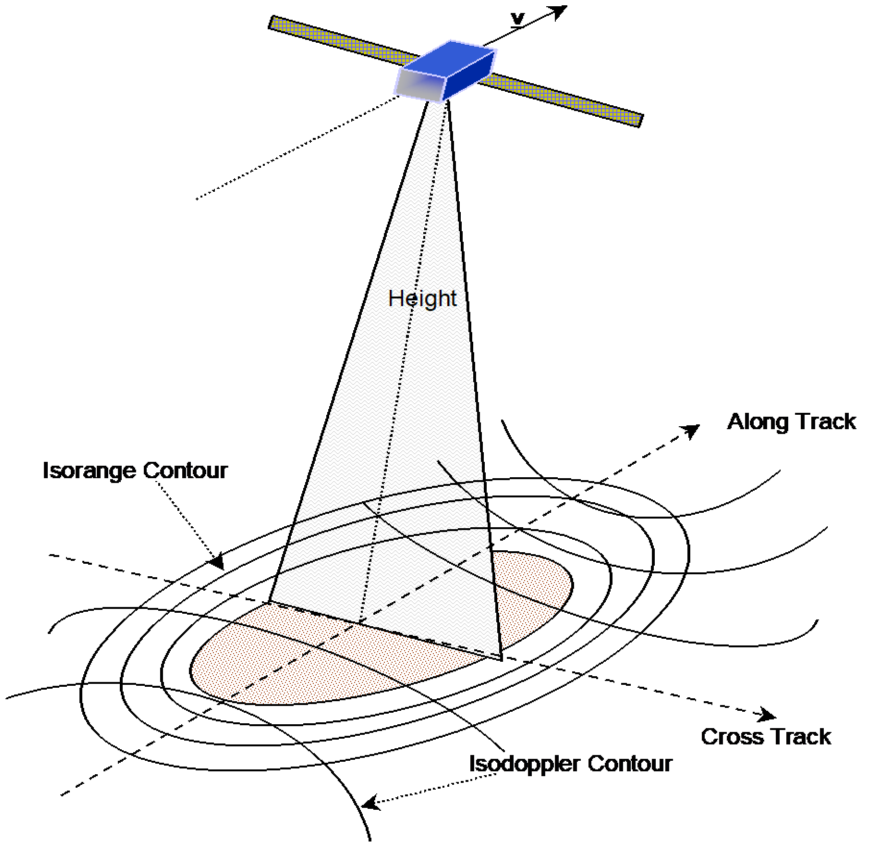
✓ The radar movement with a velocity v causes a Doppler bandwidth B_D

✓ This technique it is called Doppler Beam Sharpening (DBS)

$$\rho_H \approx \frac{v}{B_D}$$

✓ It is commonly assumed that the coherent scattering from the ground is limited by the first Fresnel zone

$$B_D \approx \frac{v}{\sqrt{2\lambda H}}$$



Radar SNR

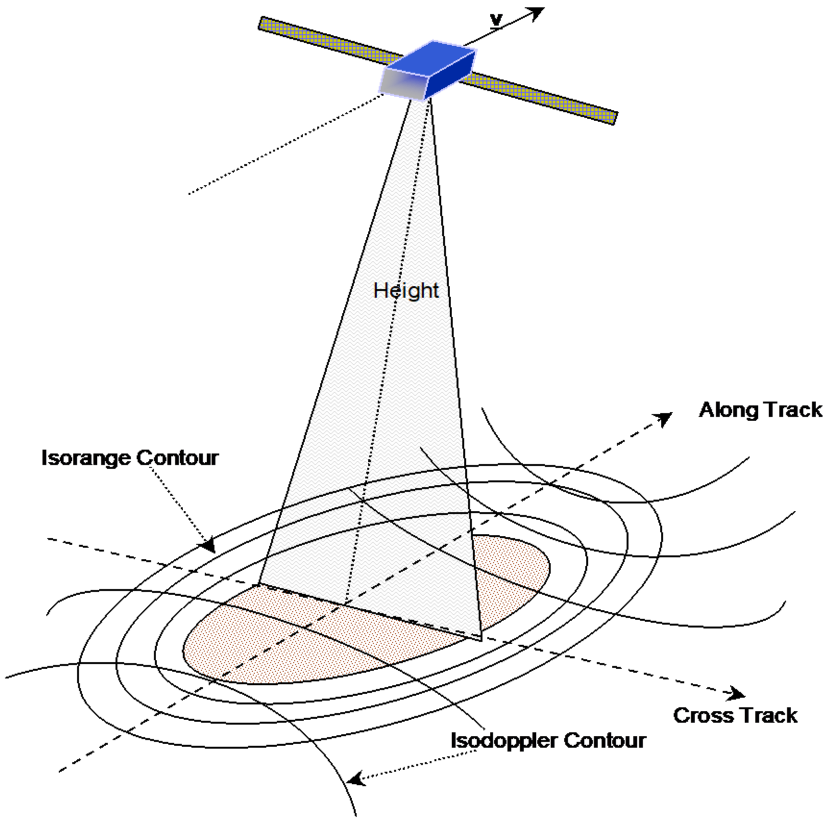
- ✓ Radar equation is a common tool for evaluating radar signal-to-noise ratio

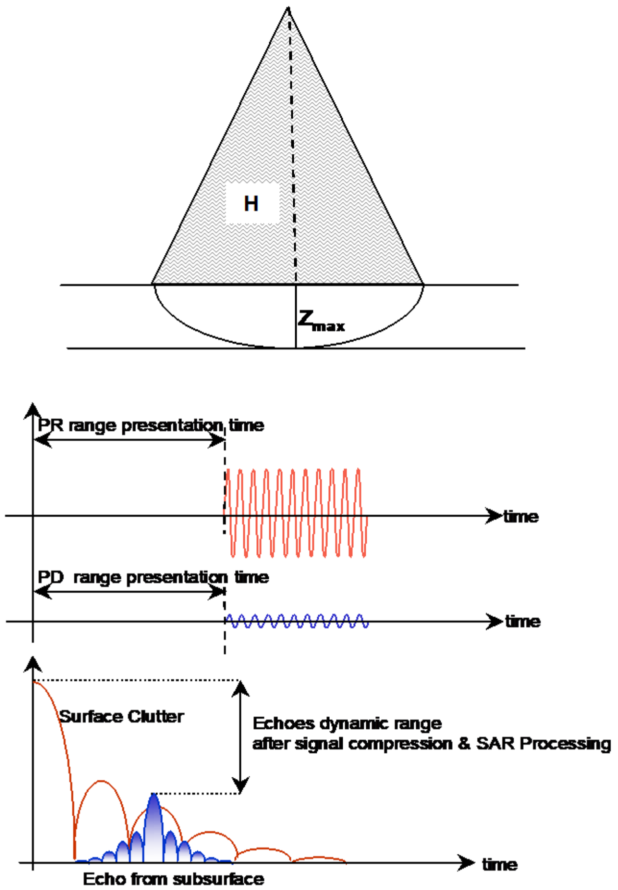
$$\frac{S}{N} = \frac{P_t G_t^2 \lambda^2 \sigma}{(4\pi)^3 R^4 k B_n T_s L}$$

- ✓ N is every noise source power. In case of thermal noise
- ✓ L are the total losses (including attenuation)
- ✓ σ is the radar cross-section of the target

SHARAD

- ✓ Doppler beam sharpening technique allows to limit clutter along-track direction
- ✓ Surface returns coming from across-track direction still limit underground detection capabilities of the instrument





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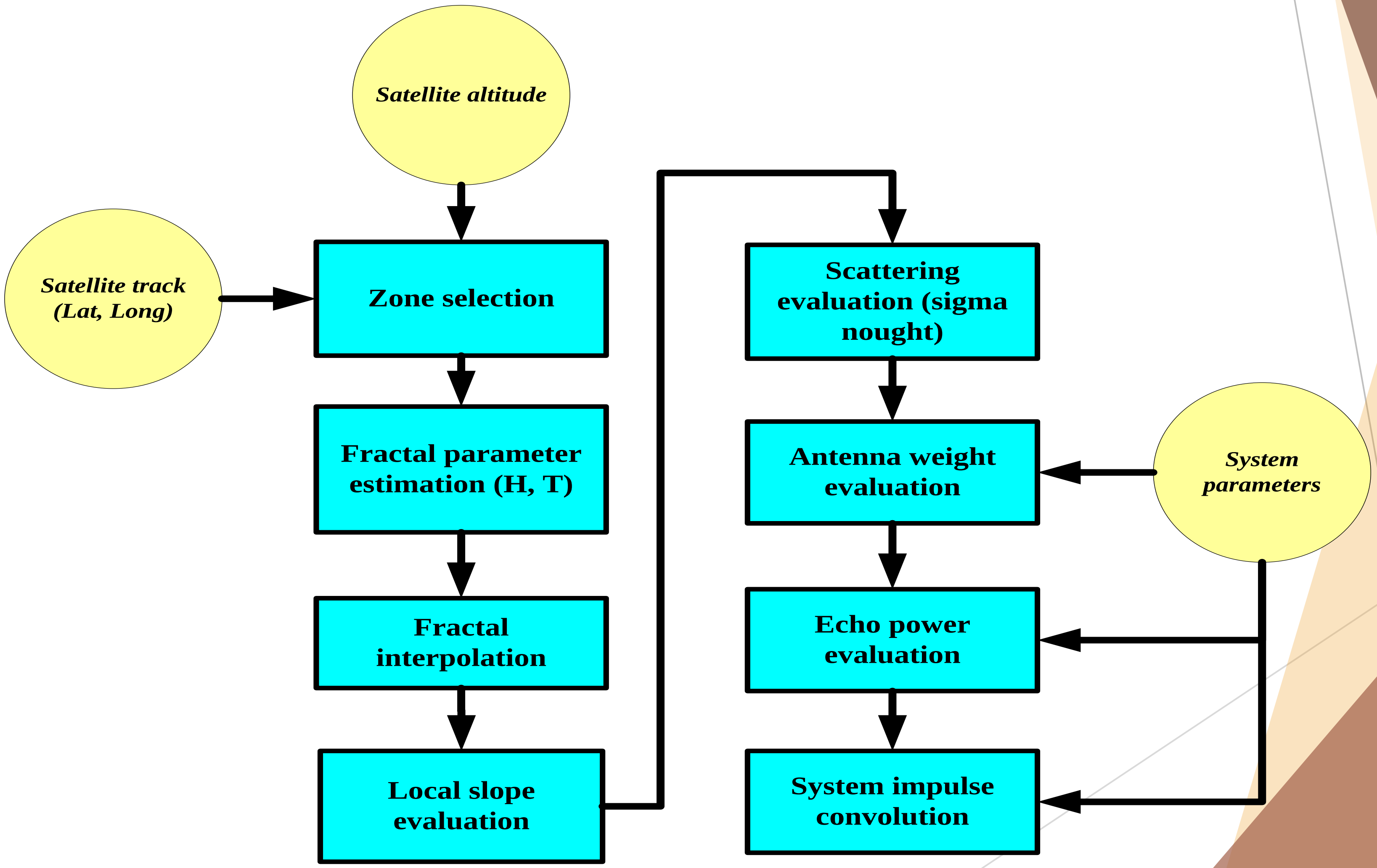
- ✓ Accurate surface simulation can help scientists to distinguish false underground targets due to off-nadir clutter



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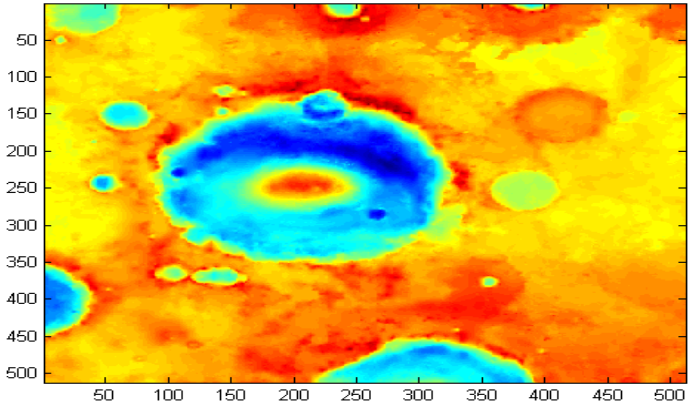
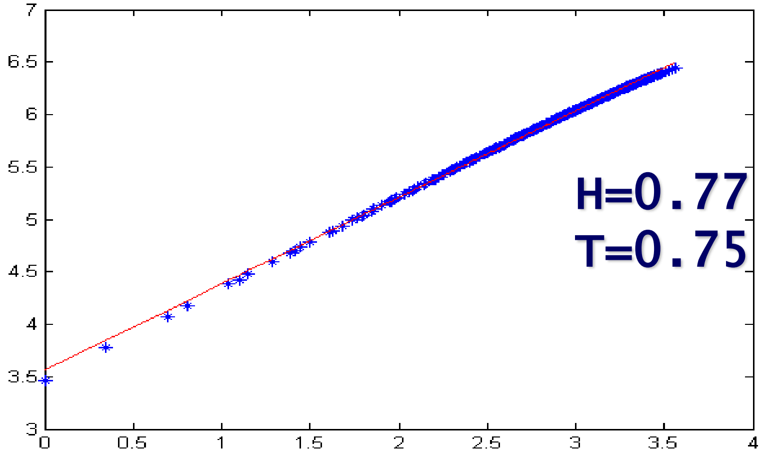
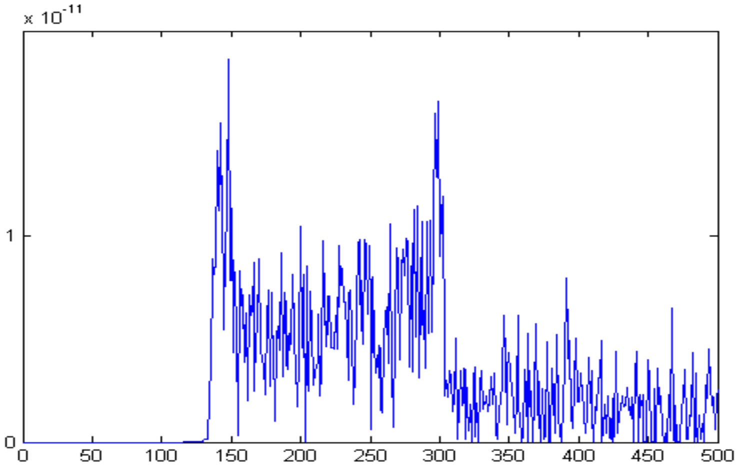
Topographic data from MOLA

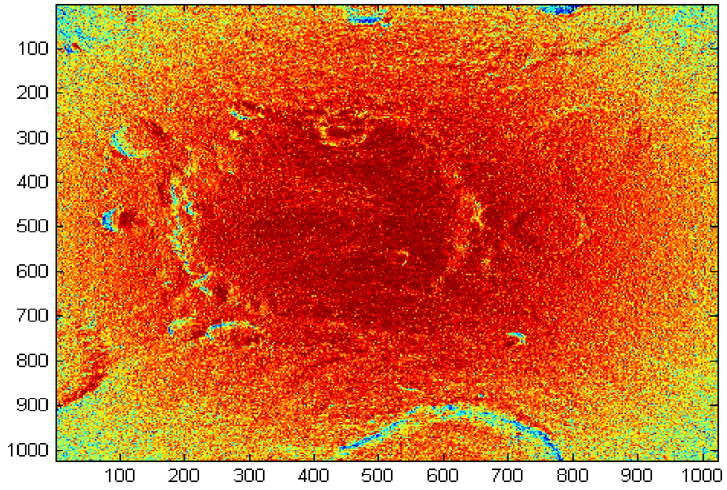




Estimation of fractal parameters



Echo simulation



Evaluation of backscattering

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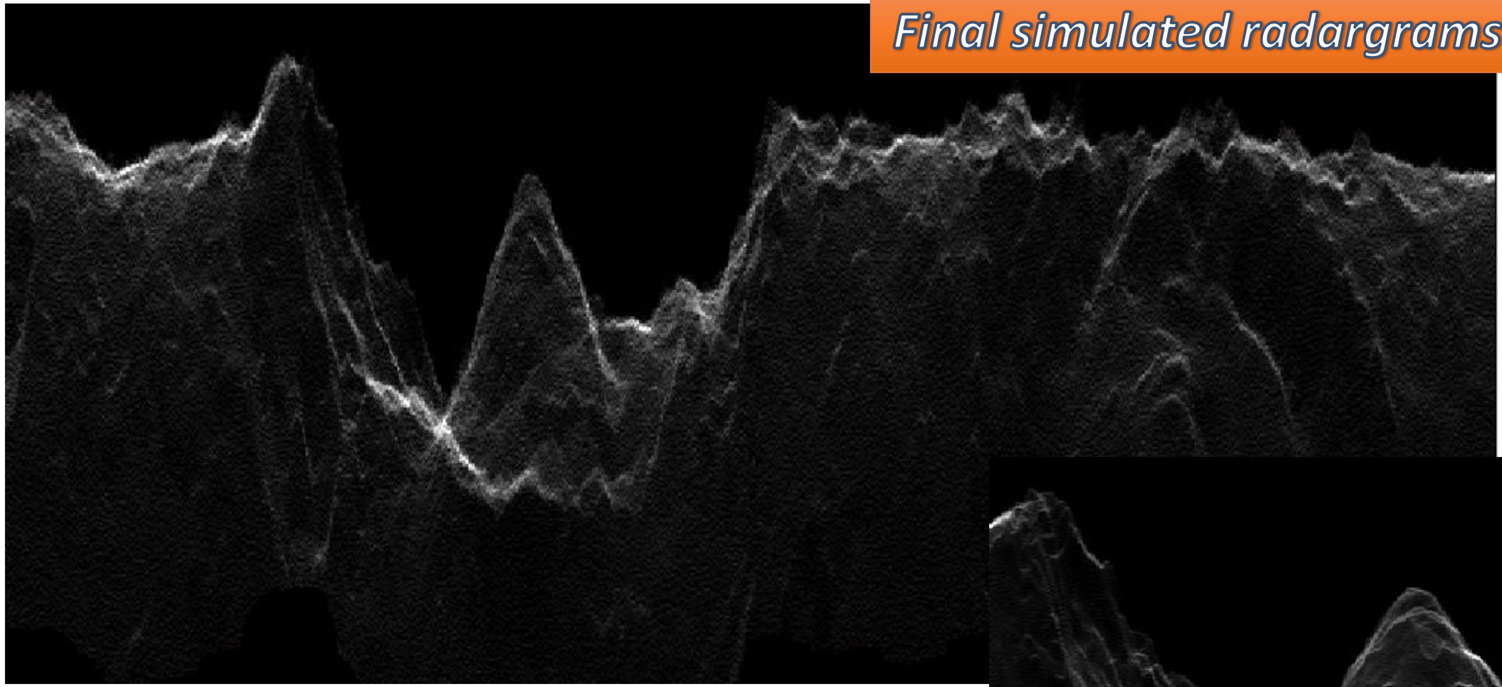
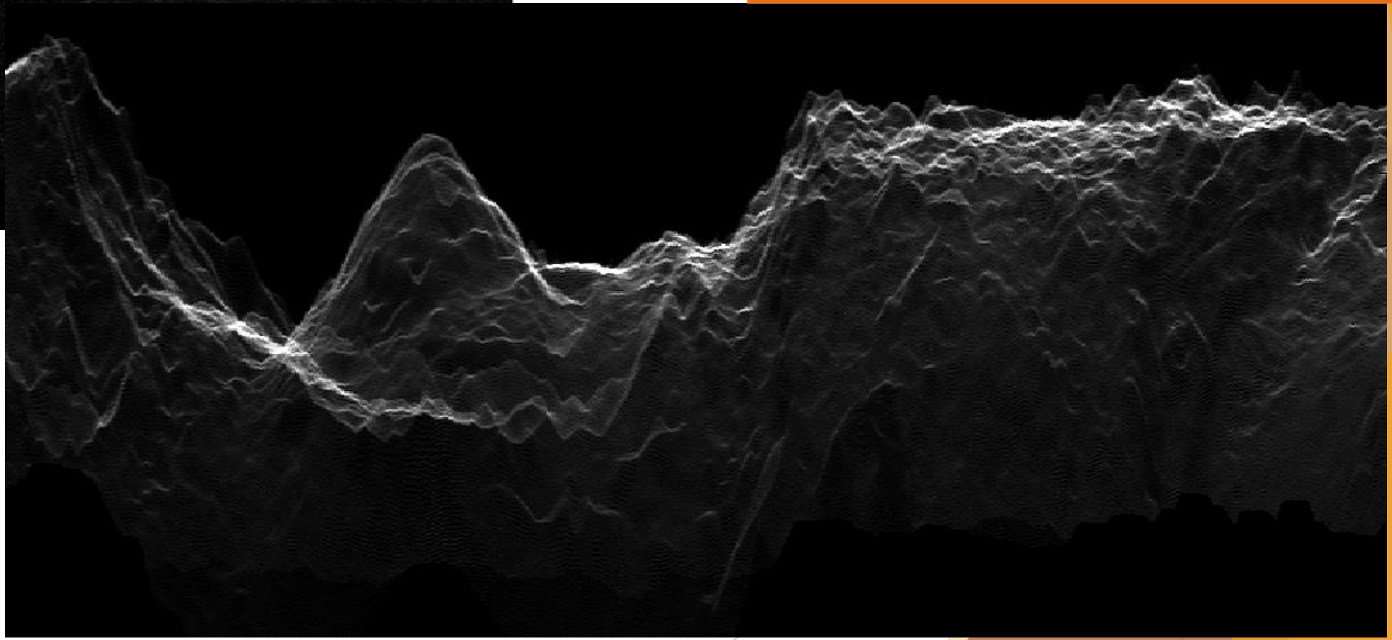
Final simulated radargrams



with high resolution DEM …



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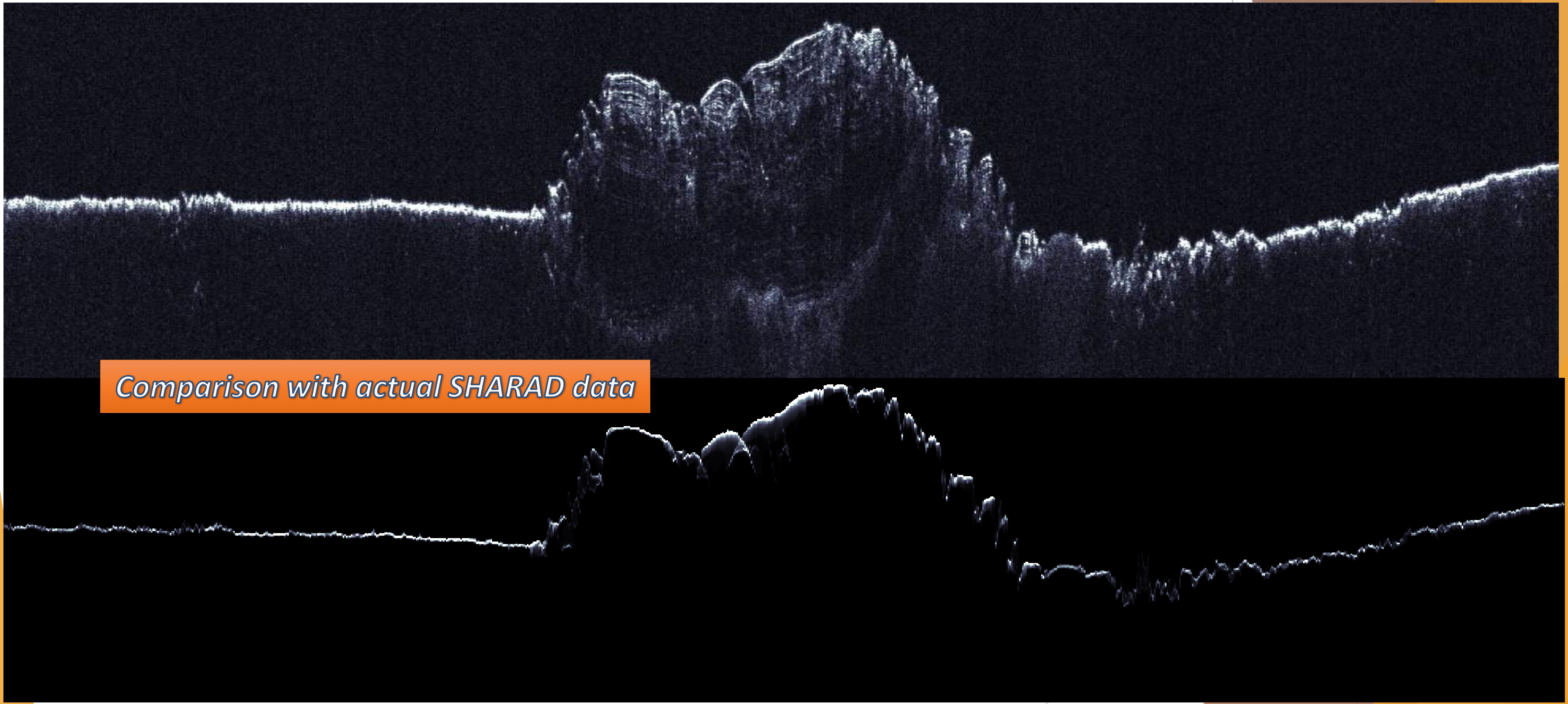

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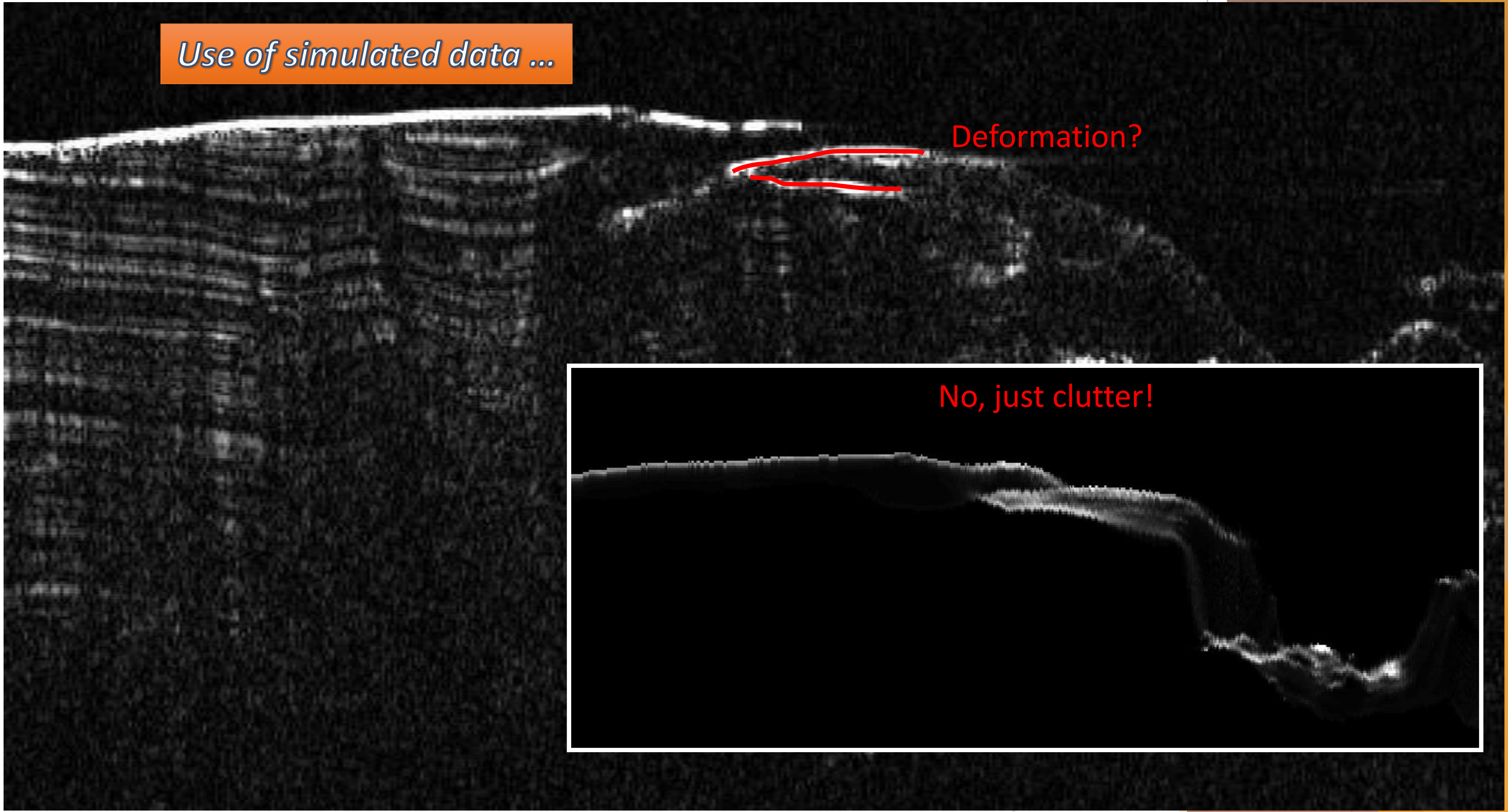

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