Planetary Exploration Radars

IPPW-9 Short Course on
Probe Science Instrumentation Technologies

R. Trautner[1]

[1]Research and Scientific Support Department (RSSD), ESA/ESTEC, Post Bus 299, 2200AG, Noordwijk, The Netherlands

Presentation Overview

- General: Radars, Configurations, Principles
- Multifunction Planetary Radars - Cassini Radar
- Planetary Subsurface Radars - MARSIS
- Bistatic Radar - Rosetta Lander CONSERT
- Descent Altimeter - Huygens Radar
- Ground Penetrating Radar - ExoMars WISDOM
- Technology, Evolution, Future Radars
- Conclusion

Radiation Detection and Ranging

Emitted power : P

Power density at target: $\frac{P * G}{4 * \pi * r^2}$ in Watt/m^2, G = Antenna gain

Power intercepted by target: $\frac{P * G * \sigma}{4 * \pi * r^2}$ in Watt, σ = target radar cross section

Power density at receiver: $\frac{P * G * \sigma}{(4 * \pi * r^2)^2}$ in Watt/m^2

Received power: $\frac{P * G * \sigma * A}{(4 * \pi * r^2)^2}$ A=Antenna effective area,

related to the antenna gain G: $\frac{4 * \pi * A}{\lambda^2}$

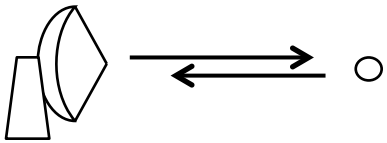
So $$P_r = \frac{P * G^2 * \lambda^2 * \sigma * A * L}{(4 * \pi)^3 * r^4}$$ L= signal losses in the system or medium

Band Designation	Nominal Frequency Range
HF	3 MHz–30 MHz
VHF	30 MHz–300 MHz
UHF	300 MHz–1000 MHz (Note 3)
L	1000 MHz–2000 MHz
S	2000 MHz–4000 MHz
C	4000 MHz–8000 MHz
X	8000 MHz–12,000 MHz
K_u	12.0 GHz–18 GHz
K	18 GHz–27 GHz
K_a	27 GHz–40 GHz

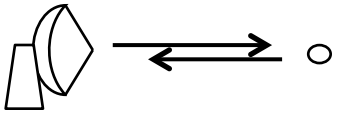
The receiver noise power is $P_n = k * T * B * F$

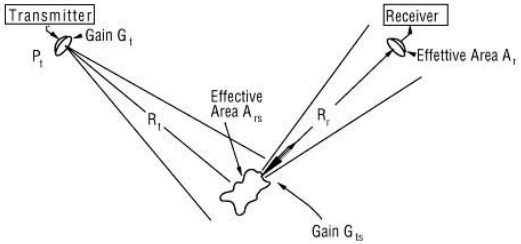
and the signal-to-noise ratio is given by $\frac{P_r}{P_n}$

k **= Boltzmann's constant**
T **= noise reference temperature**
B **= receiver bandwidth (Hz)"**
F **= receiver noise figure**



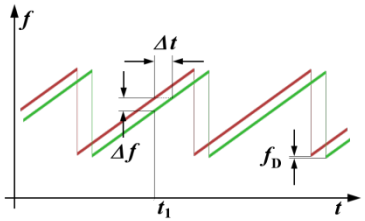
Radiation Detection and Ranging: Configurations …

●Monostatic  or Bi-static

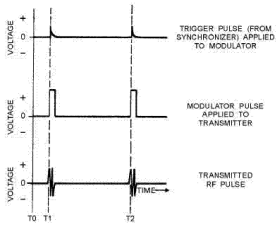


… Principles ….

●(FM)CW

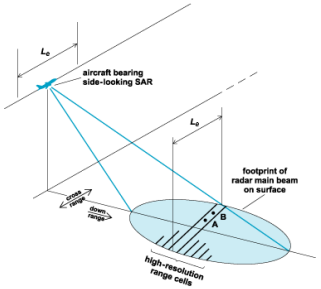


●Pulse (Doppler) Radar



… derived techniques …

● SAR



… and additional products

- Radiometry
- Backscatter / path loss / volume scatter
- Others

Frequency Modulation Continuous Wave Radar

- constant power output
- frequency modulated by waveform

Example: FMCW altimeter with triangular waveform

- received frequency mixed with transmitted freq
- difference freq is kept constant at defined IF frequency

=> triangular signal frequency prop to 1/ Alt

Applications

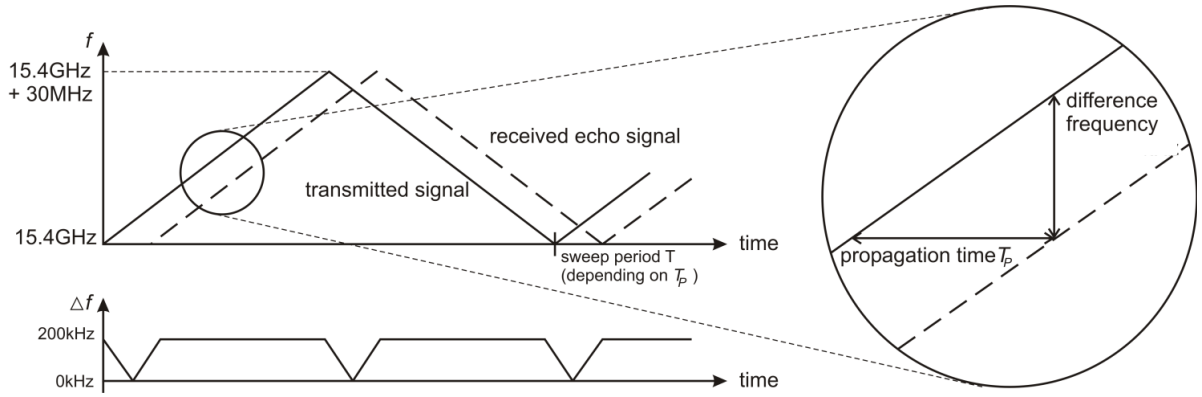
- altimeters
- cloud radars
- subsurface radars

=> simple to implement
=> light and reliable

Altitude:

$$h = \frac{1}{4}\frac{c\ df\ \Delta T}{\Delta f}$$

ΔT = sweep period,
Δf = sweep bandwidth



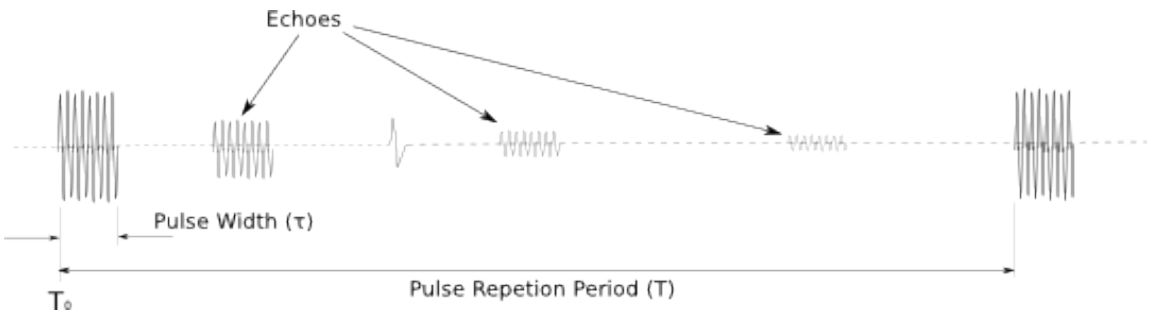
Pulse (Doppler) Radar Principle and Applications

Pulses are emitted periodically

- Time until echo is received gives distance
- Frequency shift of echo gives relative velocity (along LOS)

Note:

- Range ambiguity
- Distance
- Velocity



$$R = \frac{t_{delay} \cdot c_0}{2}$$

R is the slant range

t_{delay} is the time taken for the signal to travel to the target *and* return

$c0$ is the speed of light (approximately $3 \cdot 10^8$ m/s)

Doppler shift:

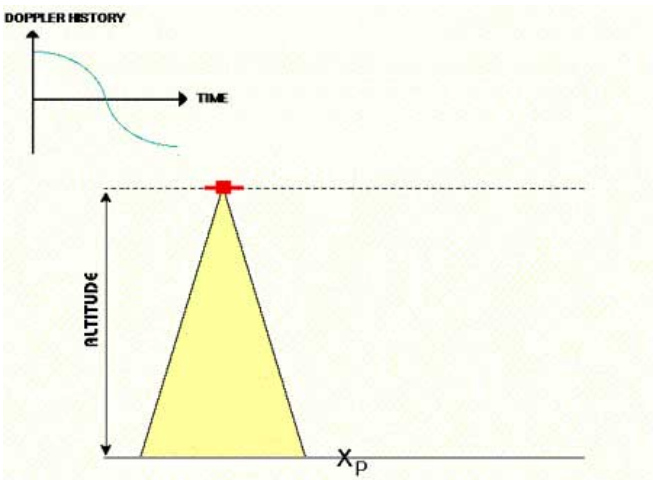
$$F_d \approx 2v\frac{F_t}{c}$$

Space Applications (various flavours):

- Altimeters
- Basis for SAR
- Subsurface sounders
- Þ Very capable instruments
- Þ More demanding wrt hardware

Synthetic Aperture Radar Principle and Applications

- Radar is emitting waveform (chirp / pulse)
- Synthetic aperture is created by using motion along orbit
- Recording and combined processing of return signals allows to generate images of reflectivity along the satellite's ground track



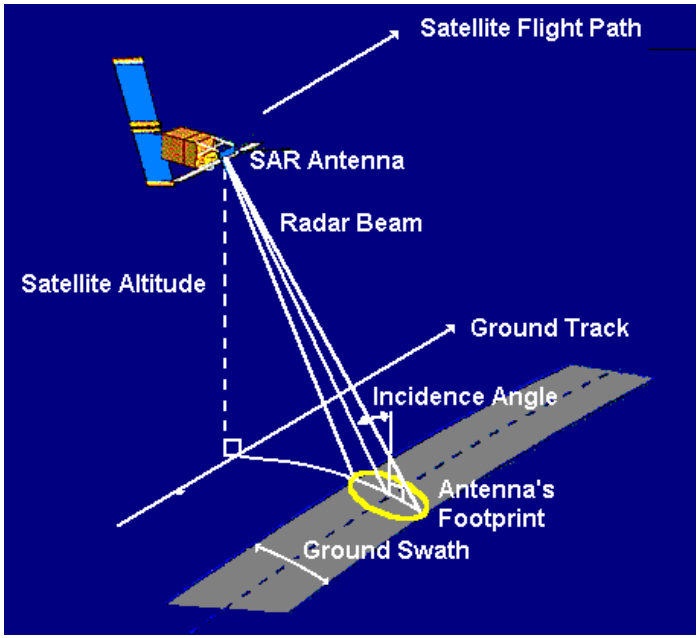


Image credit: CRISP

Applications

•Imaging through clouds / opaque atmospheres (Venus, Titan, …)

•Imaging of unilluminated surfaces in MW spectrum

Primary and secondary products

Radars are often built for a primary purpose, but can be used (and sometimes are designed) for secondary types of measurements:

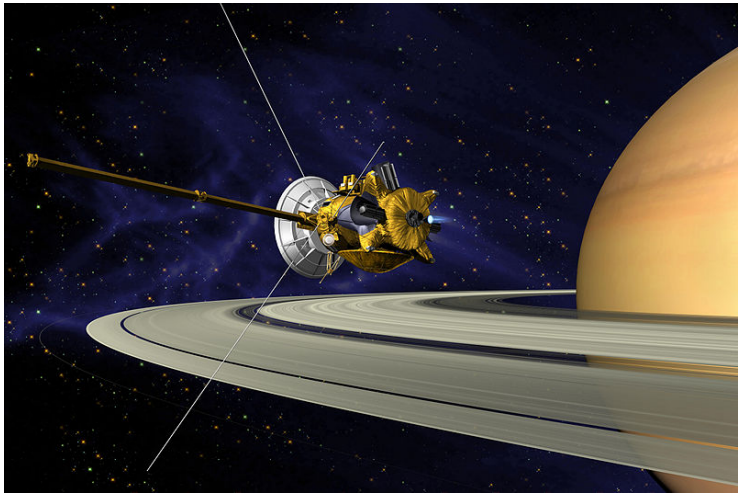
Radar type	*primary product*	*secondary products*
Continuous Wave Radar	distance, medium response (subsurface, ..)	backscatter data, volume scattering, possibly velocity / radiometry
Pulse Radar	distance, velocity, medium response (subsurface, ..)	backscatter data, volume scattering, radiometry, propagation medium properties
SAR	radar imagery	altimetry, scatterometry, radiometry data

=> These primary and secondary products will be discussed for various existing space radar systems (next viewgraphs)

CASSINI Radar
Mission and Application

CASSINI Mission

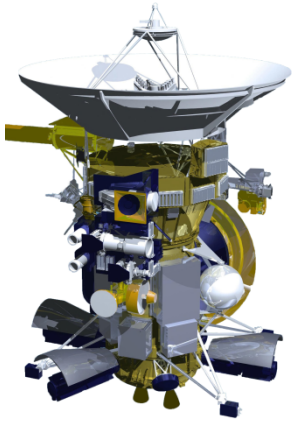
- Planetary orbiter – Saturn system
- Launched 1997, still operational
- Plasma / Atmospheric / Surface / Subsurface science during Saturn system tour
- Delivery of Huygens probe to TITAN

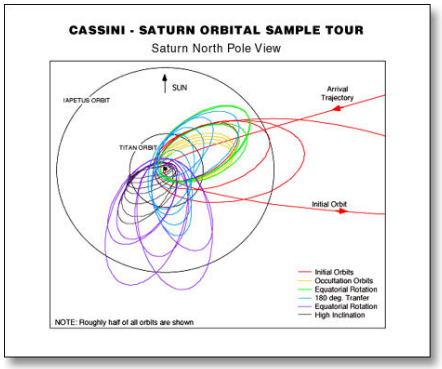


Application

Planetary science through

- Radiometer mode (passive sensing)
- Altimeter / scatterometer mode (pulse radar)
- SAR mode for surface mapping (flyby's)

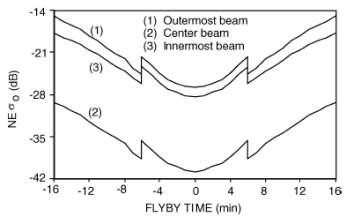


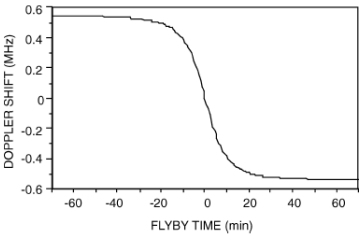


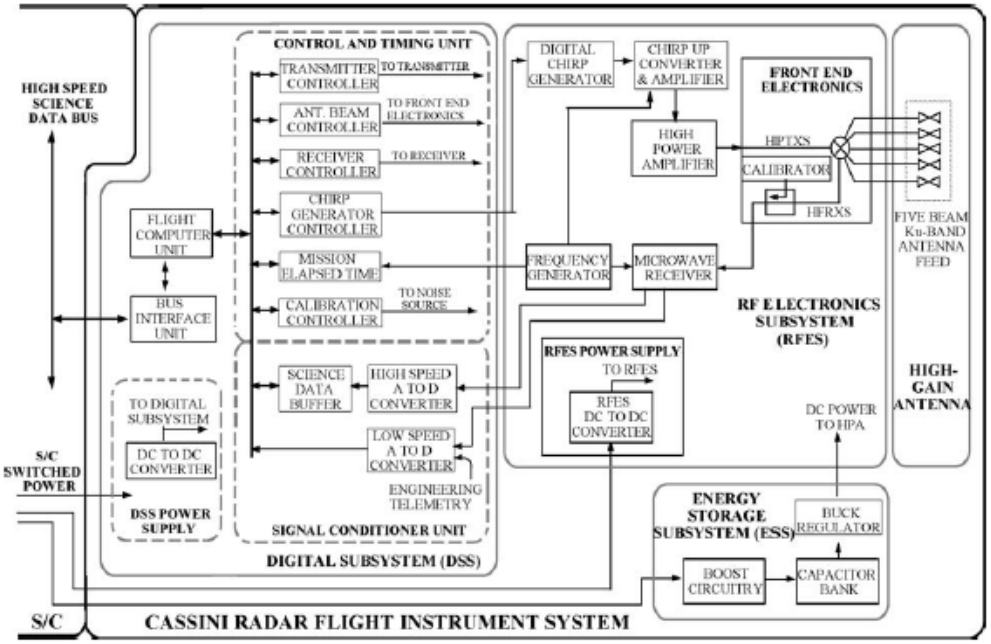
R. Trautner / ESA-ESTEC

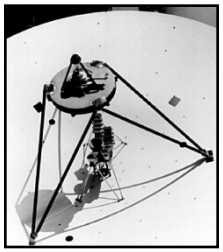
CASSINI Radar Specs

- Multi-mode multi-beam 13.8 GHz design
- Peak power 195 Watts internal, 30W from bus
- Mass 43.3 kg
- Sharing of 4m HGA
- 5-feed / 5-beam design
- Doppler compensation & range compression for chirp
- Switched Rx bandwidth









Diagrams & data from: Radar: the Cassini Titan Radar Mapper, Elachi et al, SSR 115, 2004

CASSINI radar – configuration and modes

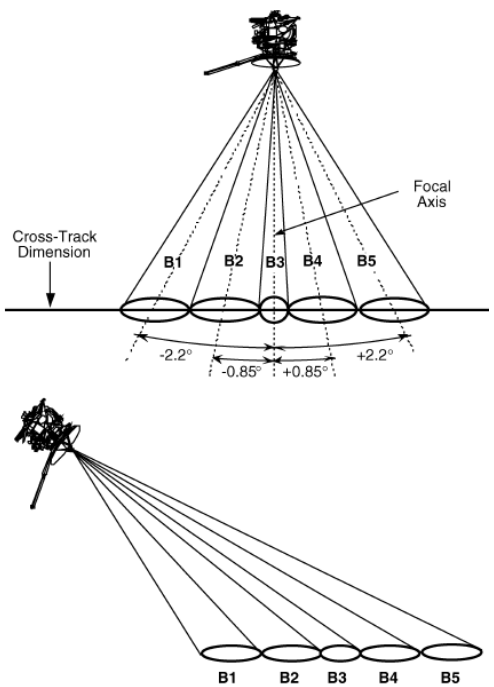


Figure 6. Antenna beam configuration for the Cassini RADAR. (*Top*): Nadir pointing for altimetry. (*Bottom*): Side-pointing for imaging.

TABLE II
System Parameters for the Cassini RADAR Modes

	Frequency (GHz)	Peak power (W)	No. of beams	Look angle (°)		PRF (kHz)	Pulse width (ms)	Bandwidth (MHz)
				Cross-track	Along-track			
Imaging	13.78	46.2	All 5	5–20	0	1.8–6.0	200–400	0.43, 0.85
Altimeter	13.78	46.2	Beam 3	0	0	4.7–5.6	150	4.25
Scatterometer	13.78	46.2	Beam 3	±6 to ±12	±6 to ±12	1.0–3.0	500	0.11
Radiometer	13.78	N/A	All 5	±6 to ±12	±6 to ±12	N/A	N/A	135

N/A: Not available.

Figures & tables from

Science & Ops

-Almost exclusively during flyby's

-Radiometry (spiral track) / altimetry (nadir track) scatterometry (nadir to limb) / imaging (side looking)

-Specific Titan objectives: physical state, topography, composition of surface; global temp and circulation

-Plus: icy satellites, Saturn rings, Saturn

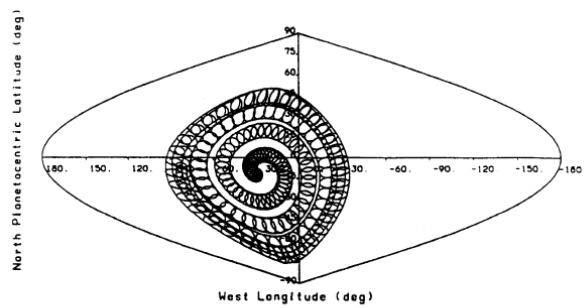


Figure 4. Scanning of Titan with the RADAR central beam. (*Top*): Constant cone angle; distance 100,000 km–10,000 km, clock rate 0.05° s^{-1}. (*Bottom*): Variable cone angle; distance 80,000–25,000 km, clock rate 0.20° s^{-1}.

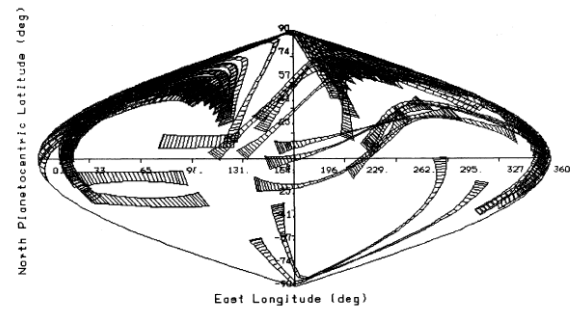
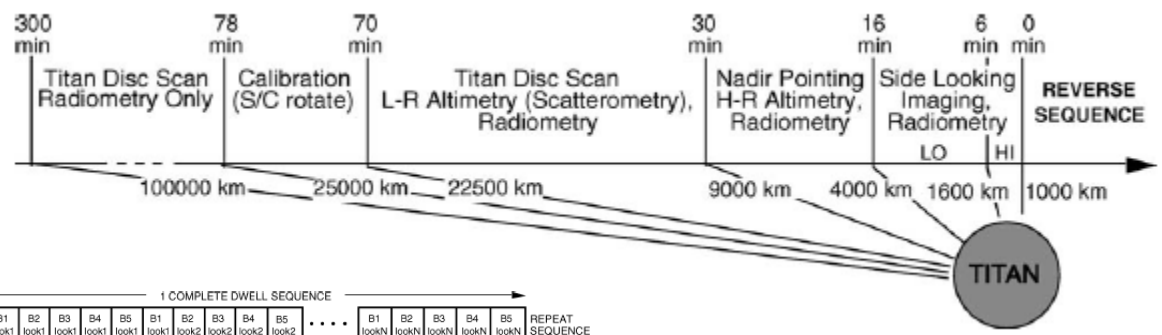
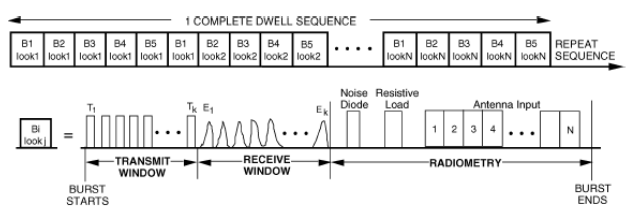


Figure 3. Mapping of Titan in the RADAR high- and low-resolution imaging modes. Included are only flybys with the close-approach altitudes <4,000 km; incidence angle 20°. (*Top*): Tour 18-5, (*Bottom*): Tour 19-1.

Radiometry / SAR mapping





Ops modes and - interleaving

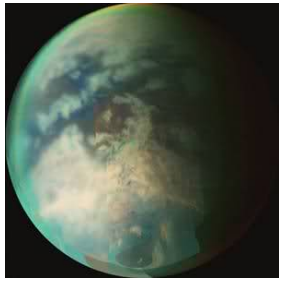
Some selected Science results …

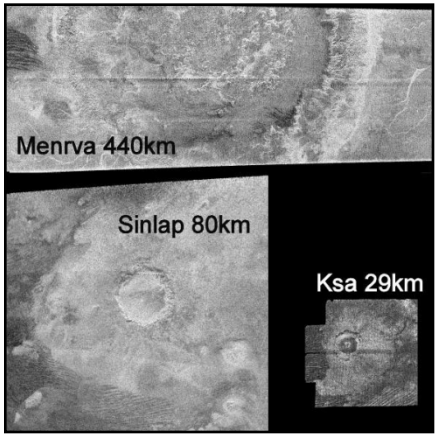
Maps of shrouded Titan surface

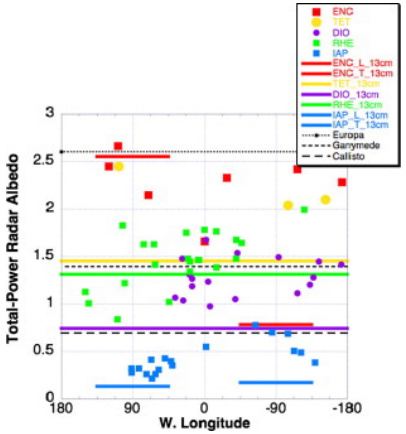
Discovery of impact structures / craters

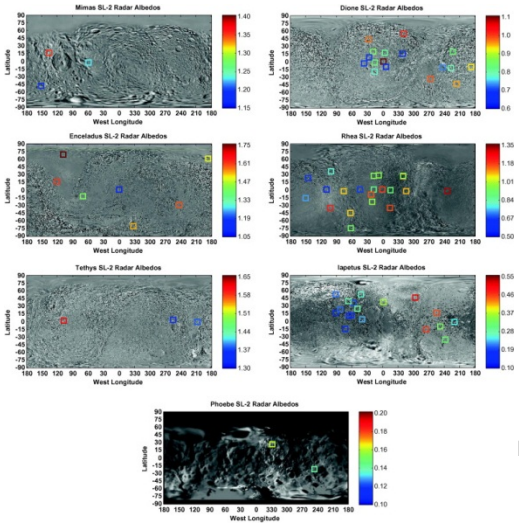
Lakes, glaciers, dunes on Titan

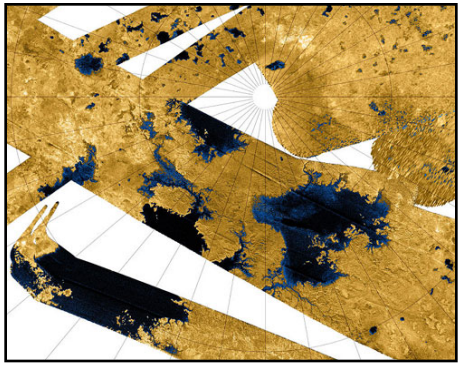
Radar albedo, surface properties of moons etc. etc.









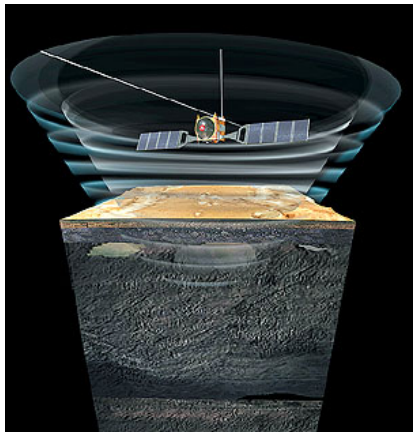


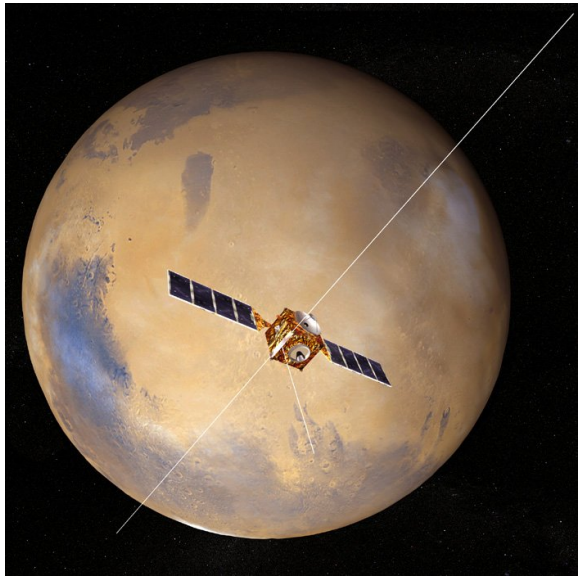
Images from selected publications (Ostro et al, Lorenz et al, Aharonson et al)

MARSIS Subsurface Radar Mission and Application

Mars Express Mission

- Planetary orbiter
- Launched 2003, still operational
- Plasma / Atmospheric / Surface / Subsurface science
- Beagle 2 lander († 2003)

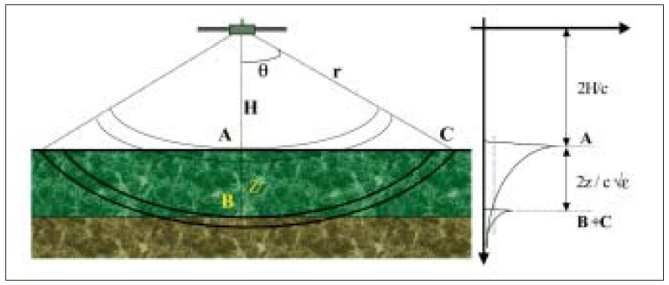


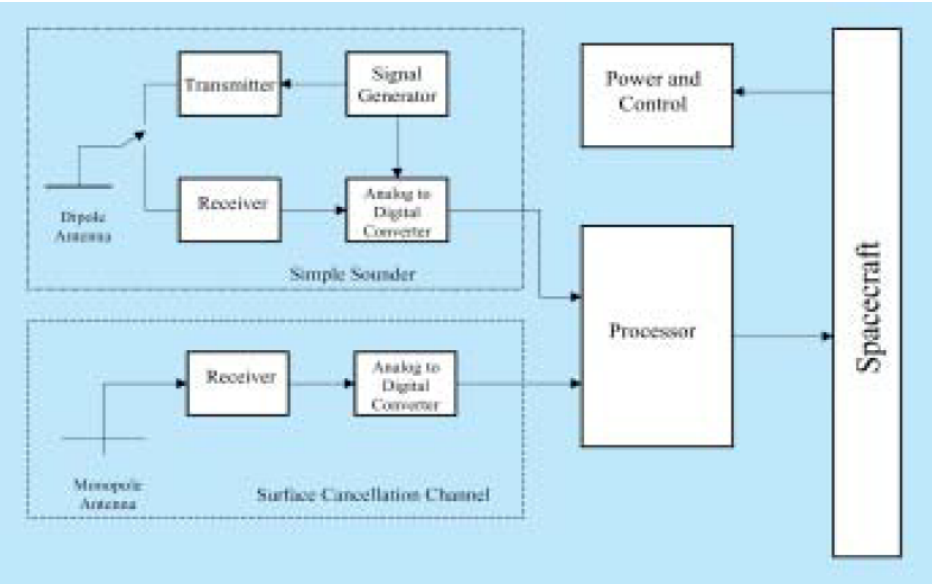


Application:

- Planetary subsurface science
- Surface / crust characterization
- Ionospheric sounding

MARSIS Subsurface Radar Design & Function





Key specs:

F = 1.8/3.0/4.0/5.0 MHz, B=1 MHz
P = 1.5/5/5/5 Watts
Pulse width 250 usec
Min alt = 250 km
PRF 130/sec
Footprint ~ 10km ⌀, ~ 5 km depth range, 100m depth resolution
Dipole antenna 20m, monopole 7m
Mass 17 kg
Power max 64.5 Watts

Table 1. Dielectric properties of the subsurface material.

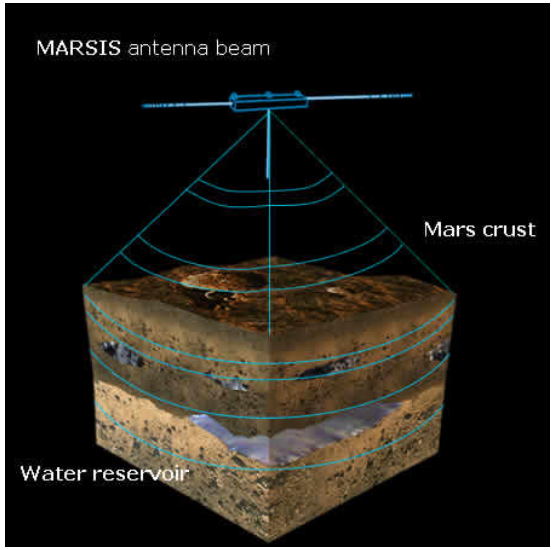
	Crust Material		*Pore-Filling Material*	
	Andesite	*Basalt*	*Water Ice*	*Liquid Water*
ε_r	3.5	7.1	3.15	88
tan δ	0.005	0.014	0.00022	0.0001

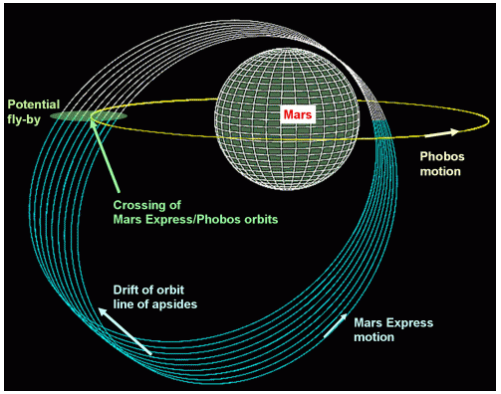
See: Mars Express-The Scientific Payload, ESA SP-1240, 2004

MARSIS Subsurface Radar Operations & Science

Key science objectives

- Map distribution of solid & liquid water in upper crust
- Surface geologic probing, surface characterization, ionospheric sounding
- Current/past inventory of water
- Study water transport, storage
- Evolution: geology, climate
- Surface roughness, topography
- Ionospheric sounding: e^- density



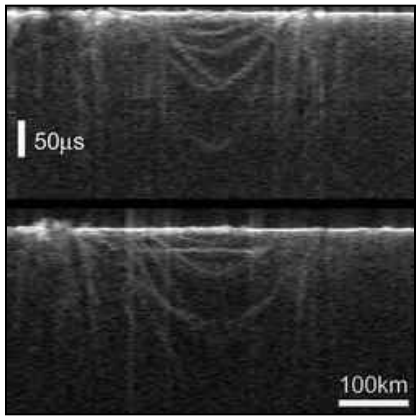


- Subsurface sounding below 800km altitude (26' per orbit)
- Ionospheric sounding at up to 1200 km

MARSIS operations

- Data rate 18 – 75 kbps
- Daily data volume max 285 Mbit
- Near-polar (86 deg inclination) orbit
- Periapsis 250 km, apoapsis 10140 km

MARSIS Subsurface Radar Science Results



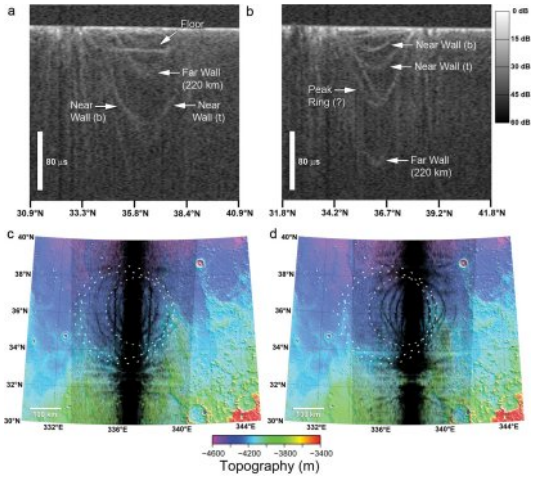
Buried imact crater (left),

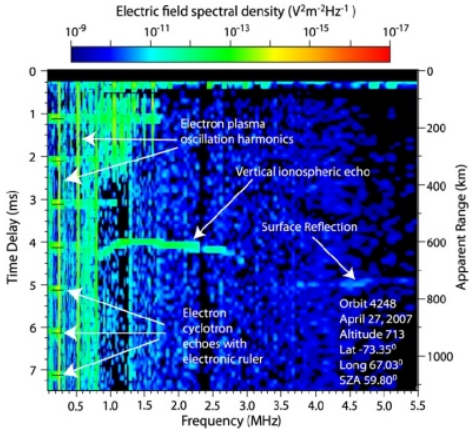
Ionogram (below left),

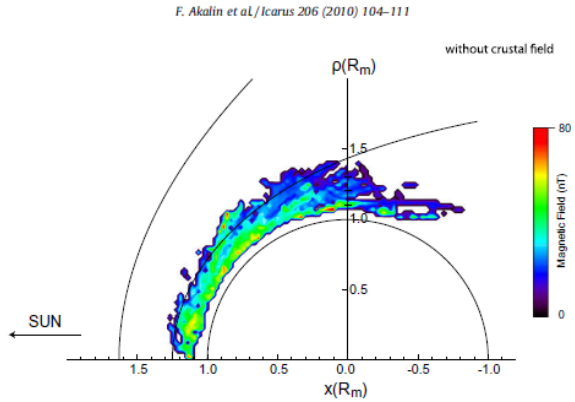
Magnetic field data (center)

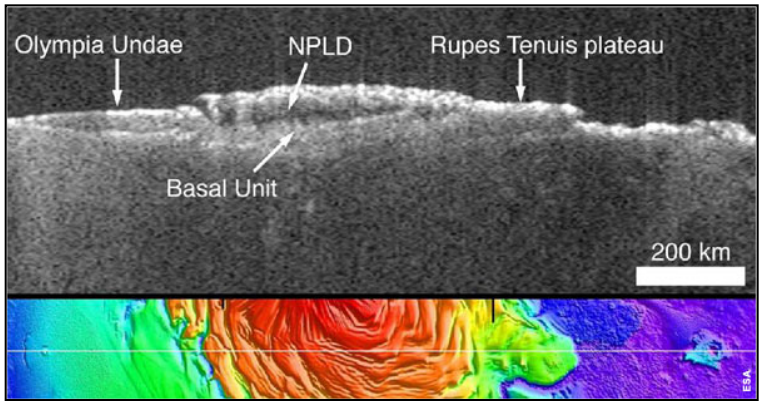
Polar subsurface interfaces (below right),

Buried basins (right)





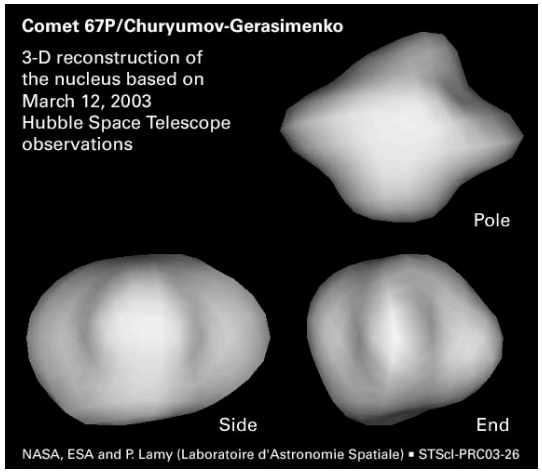




CONSERT Radar
Mission and Application

Rosetta / Philae Mission

- Cometary orbiter for Churyumov-Gerasimenko (⌀ 4km, t=12.3 hrs)
- Launched 2004, operational; arrival May 2014
- Plasma / Nucleus surface & subsurface science during comet orbiting phase
- Delivery of Philae lander on cometary surface – Nov 2014

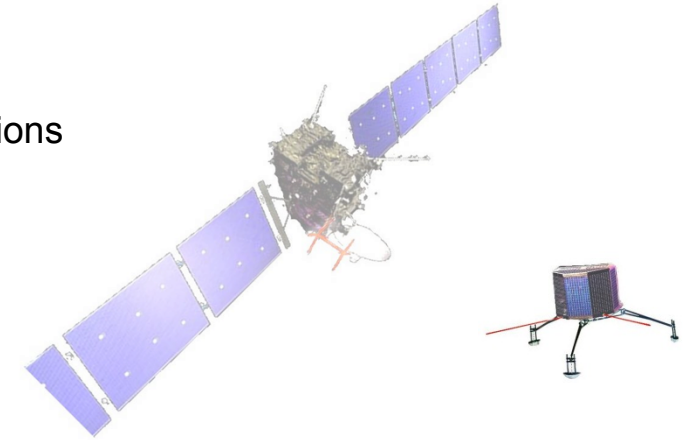


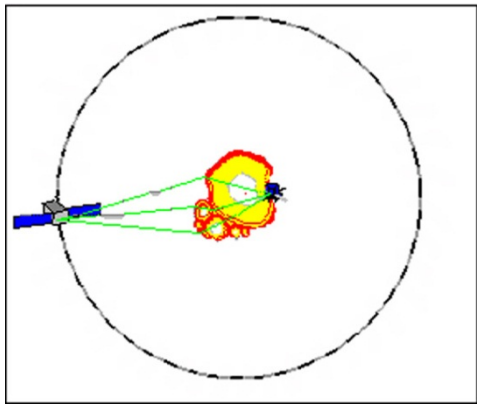
Application

Bi-static radar investigations of cometary nucleus

Orbiter: Sync Tx/Rx

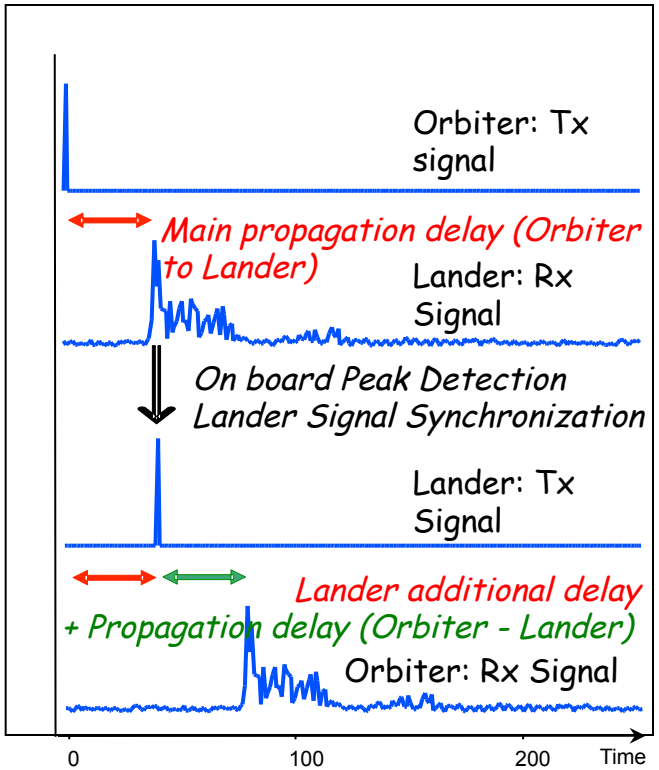
Philae: Sync Rx/Tx

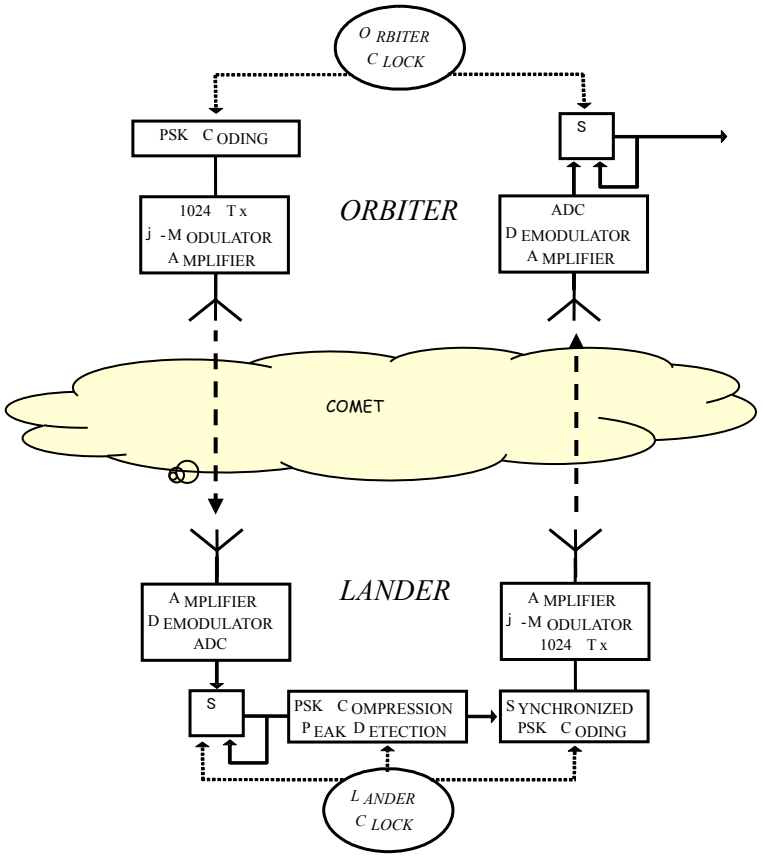




Credits: W. Kofman / Laboratoire de Planétologie de Grenoble actuellement IPAG)

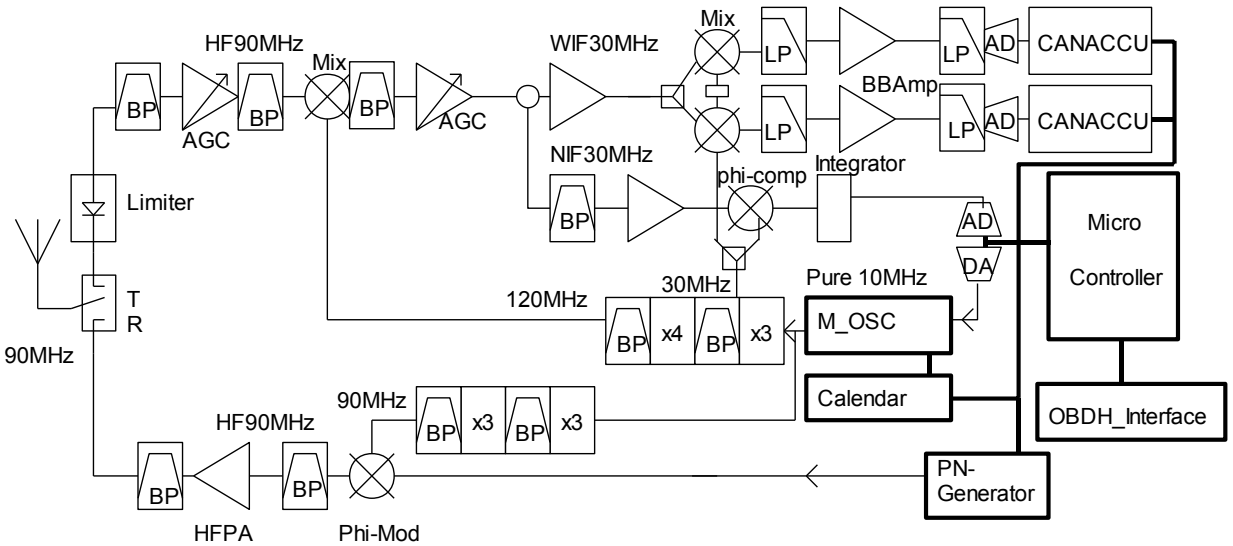
Comet Nucleus Sounding Experiment by Radiowave Transmission (CONSERT)





Credits: W. Kofman / Laboratoire de Planétologie de Grenoble actuellement IPAG)

CONSERT Radar Design & Function (2)



- 90 MHz carrier
- Step code : 100 ns (10 MHz clock)

Two ways experiment

- On way for synchronization
- One way for science measurement
  - Additional delay
  - Ground compensation

Clock constraints

- Time preservation during calculation time (ms)
- Tx/Rx windows (ms) versus orbit
- Phase coherence during integration
  - $\Delta f/f = \sim 10^{-7}$

Credits: W. Kofman / Laboratoire de Planétologie de Grenoble actuellement IPAG)

CONSERT Radar Design & Function

PSK coded Signal

- Step 100 ns (B = 10MHz)
- 90 MHz Modulation
- 25,5µs per code
- Periodic signal

Processing

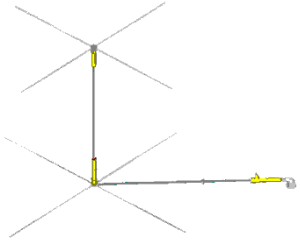
- I,Q demodulation
- 1024 accumulations (SNR +30 dB)
- Matched filter (+24 dB)
- Peak detection (maximum power)

Measurement cycle: 0.5 s

- Tx = 200 ms, Rx = 26 ms, Processing 200 ms

Antennas: Circular polarization

- Orbiter: Cross –Dipole + reflector
- Lander: 2 monopoles

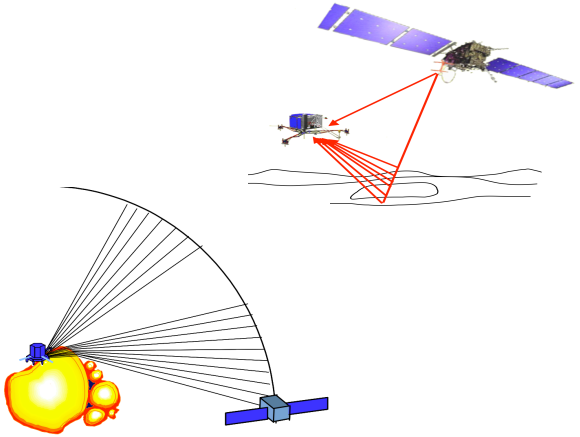


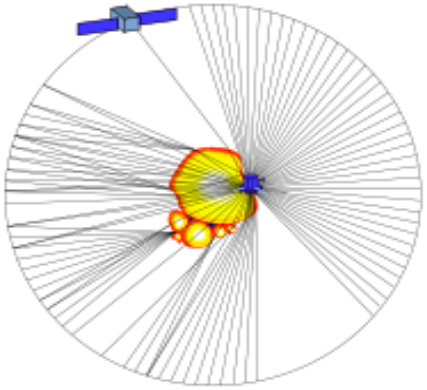
	Orbiter	Lander
E box	1.5 kg	1.5 kg
Antennas, Harness	1.5 kg	0.8 kg
Volume	1.5 l	1.5 l
Mean power	3 W	3 W
RF power (Tx)	2 W	0.2 W

Credits: W. Kofman / Laboratoire de Planétologie de Grenoble actuellement IPAG)

Science Objectives:

- **Probe the interior and surface** of the cometary nucleus
- **Measure mean permittivity** to identify electrical properties via group delay measurement
- **Classify material** from absorption
- **Identify internal interfaces**, irregularities / small structures, determine size of cometesimals / build up tomographic image of interior via many orbits (correlation length of the measured signal as a function of the orbit position is related to the size of the irregularities or small structures inside the comet; temporal structure of the received signal, the number of different paths and their variation with the propagation path are related to the size of the cometesimals and to the reflection coefficient at internal interfaces)
- Measure the **volume scattering coefficient** which provides info on the homogeneity of the interior of the comet nucleus
- **Range measurements** (~ 3m accuracy) between orbiter and lander for observing gravitational & non-gravitational forces

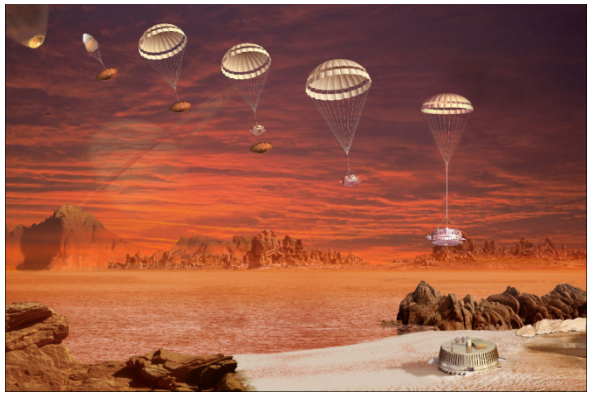


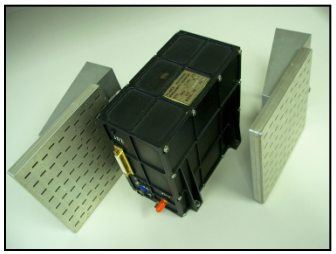


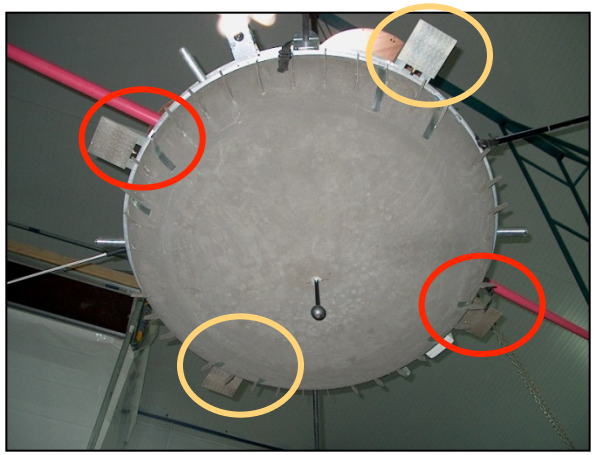
Huygens Radar Altimeter: Mission and Application

Huygens Mission

- Launch 1997, arrival 2005
- Separation from Cassini & unpowered cruise towards Titan
- Timers activate essential probe functions
- Atmospheric entry, triggers via ACC
- Probe systems activation (parachute / boom deployments, etc)
- Activation of radars & payloads



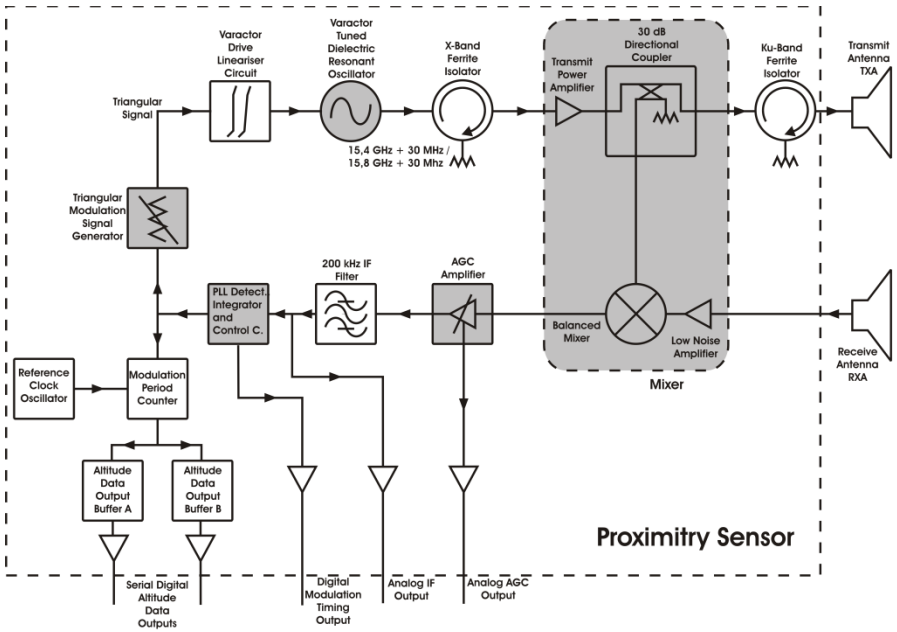




Application

- measurement of altitude in order to activate payloads correctly according to their scientific mission
- Provision of signals to HASI payload for addressing additional science goals

Huygens HRA
Design & Function



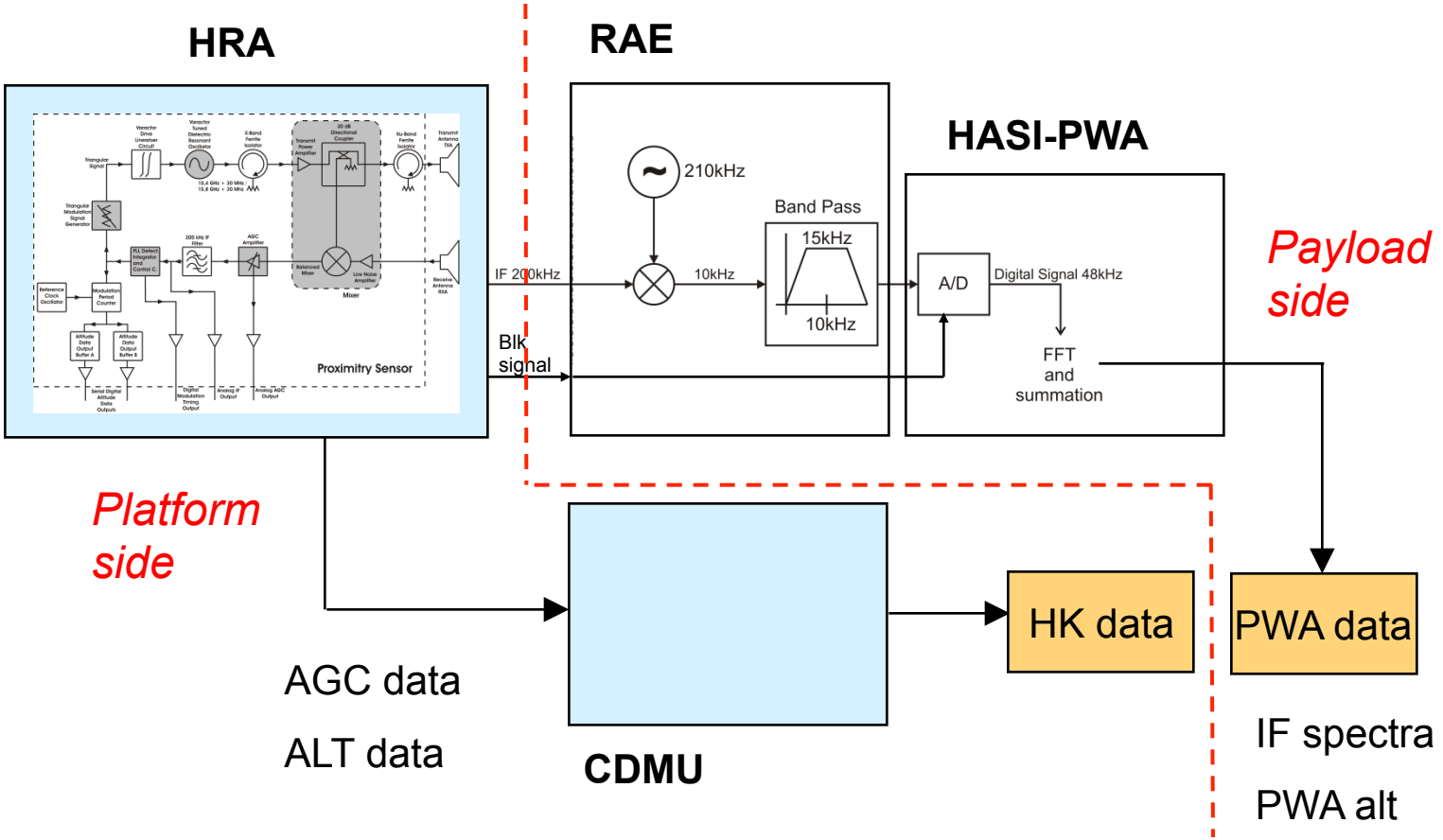
HRA design features

- Probe system, redundant, 1990ies
- Mass: 2 kg (1 unit, incl 2 antennas)
- Power: 4.2 Watts (1 unit)
- Tx frequencies 15.4 GHz, 15.8 GHz
- Output power ~ 100 mW
- FM bandwidth 30 MHz
- Planar slot antennas with 26 dBi gain
- 15 kHz IF BW, 200 kHz IF freq
- 50 dB AGC gain range
- Design alt range 150m to 10 km (initial), up to ~ 60 km (after modifications)

Data products

ALT data (digital interfaces), AGC data (analogue HK), IF data (HASI-PWA science)
Scientific utilization was result of Huygens PS initiative - late implementation

Huygens HRA
Interfaces & data processing



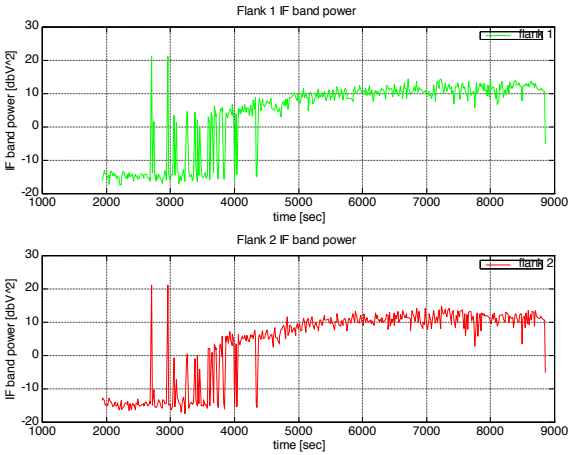
Altimetry and Surface Backscatter

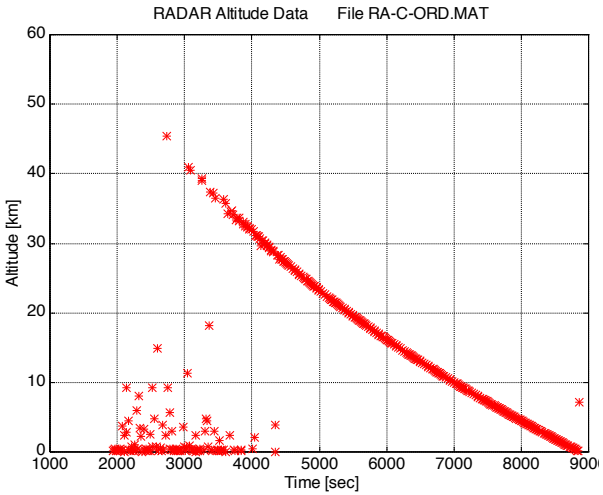
FMCW ramp rate → Altitude → Backscatter coefficient

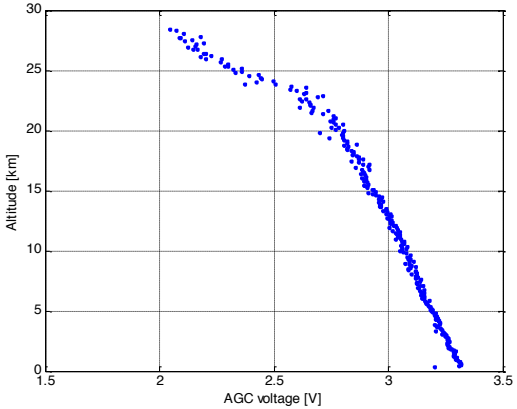
IF spectral power

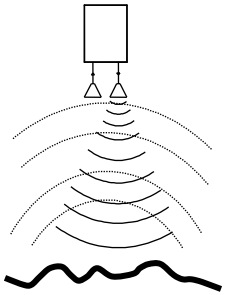
AGC voltage → RX power

TX power

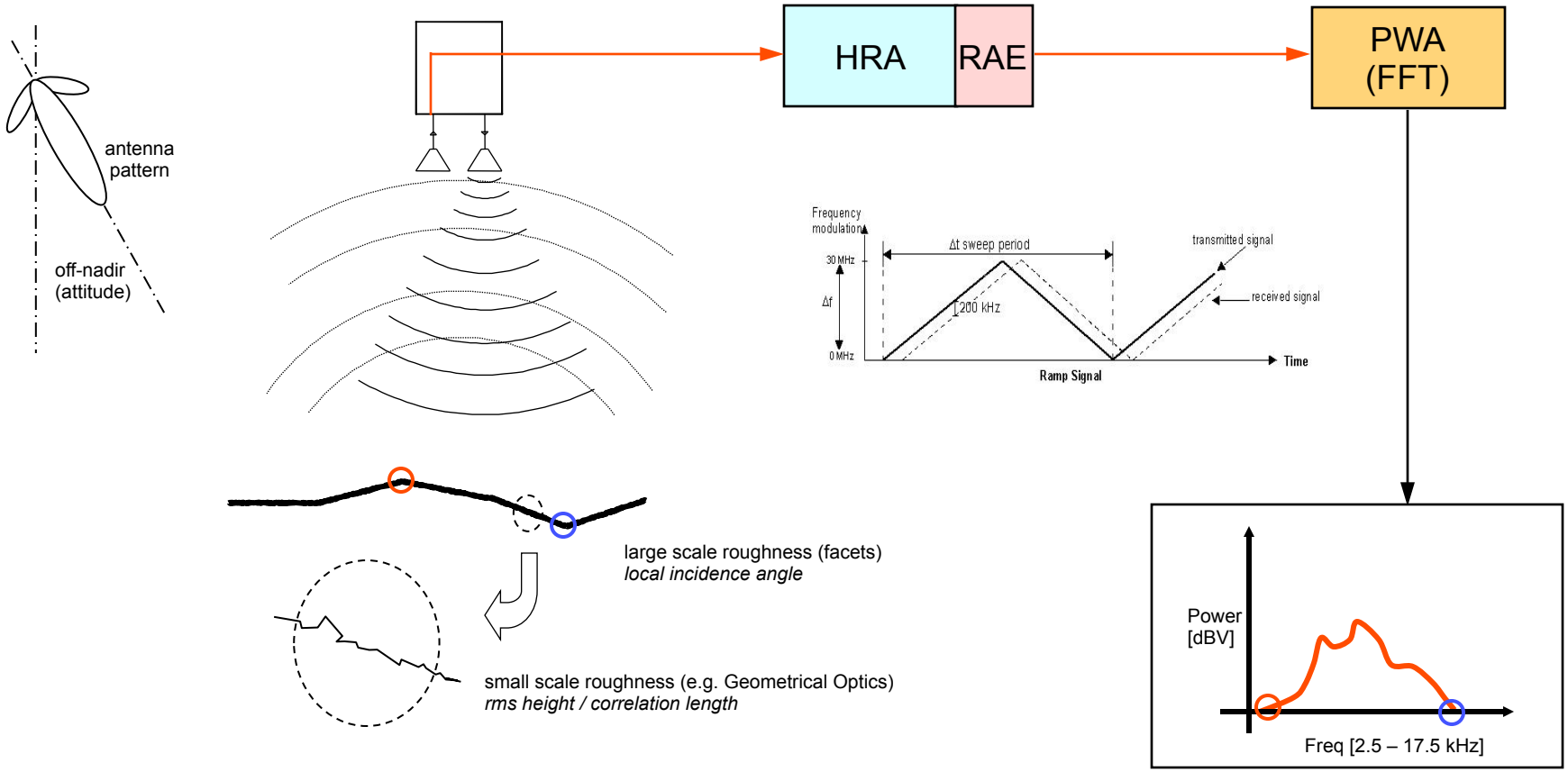




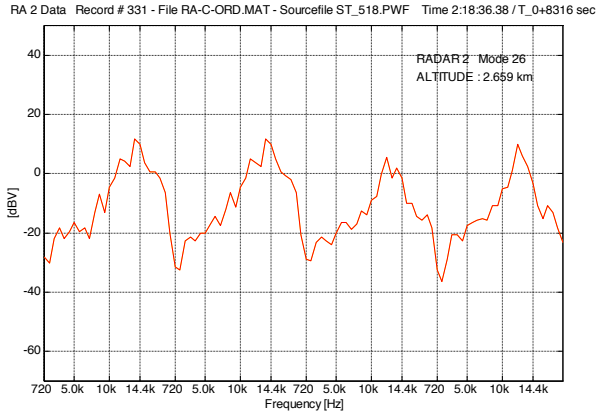


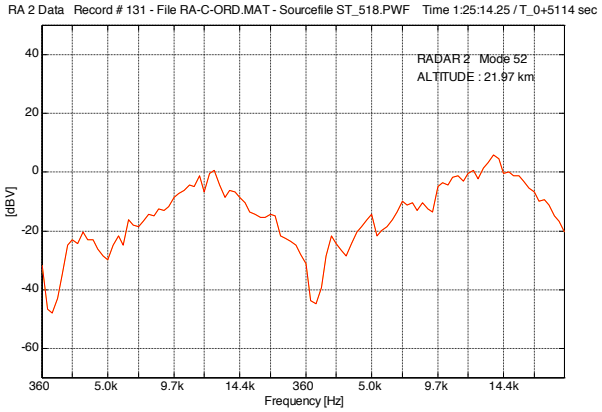


Surface topography and spectral data (1)

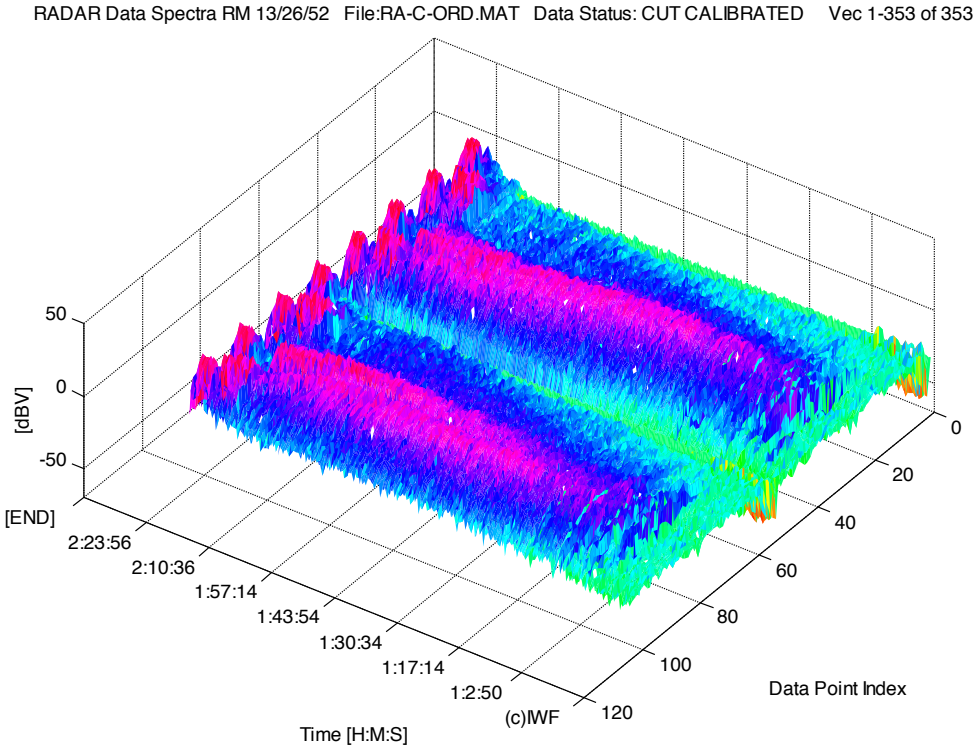


Surface topography and spectral data (2)

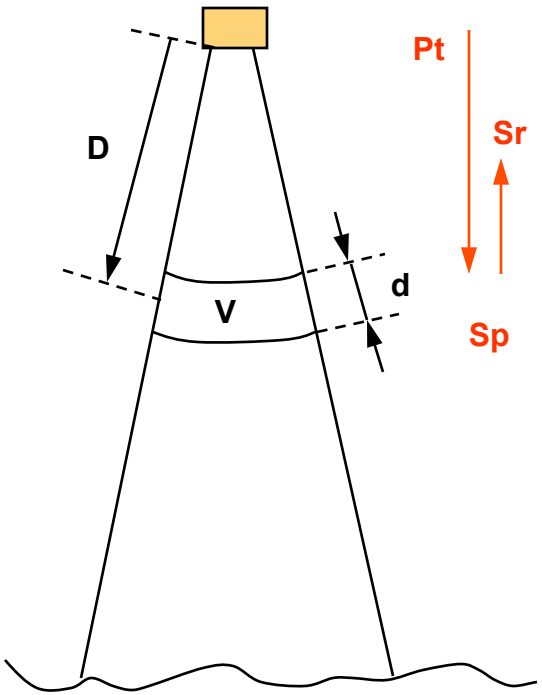




Huygens data:
Individual radar return spectra and dataset overview



Atmospheric backscatter measurements (1)



Emission and backscatter

Pt: transmitted power
Sp: prop. $1/D^2$
Sr: prop. $1/D^4$ for 1 particle
V: prop. D^3

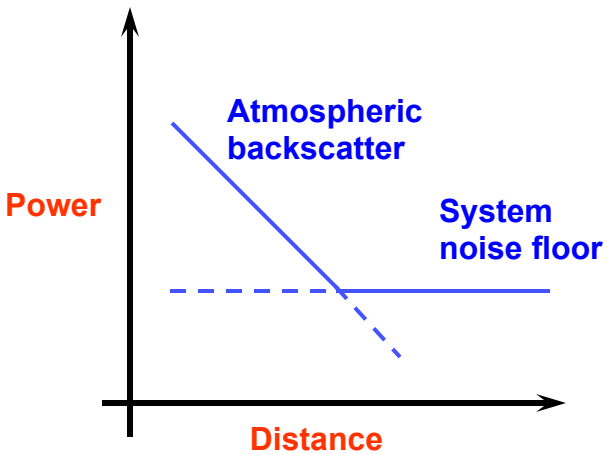
ÞSr prop. 1/D , Pr prop 1/D
for backscattered signal

Important factors:

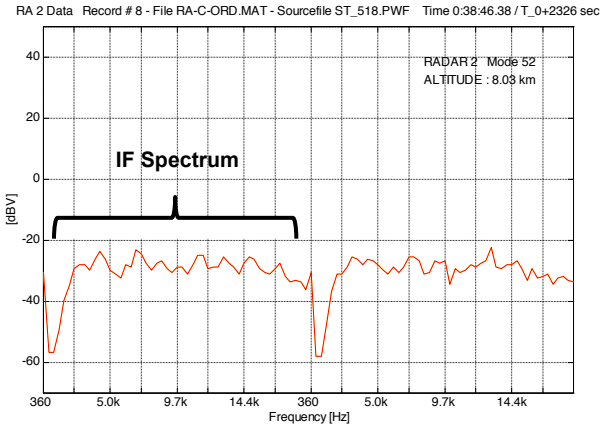
- Transmitted power
- Z – factor (total backscatter cross-section)
- Receiver chain noise level and interference

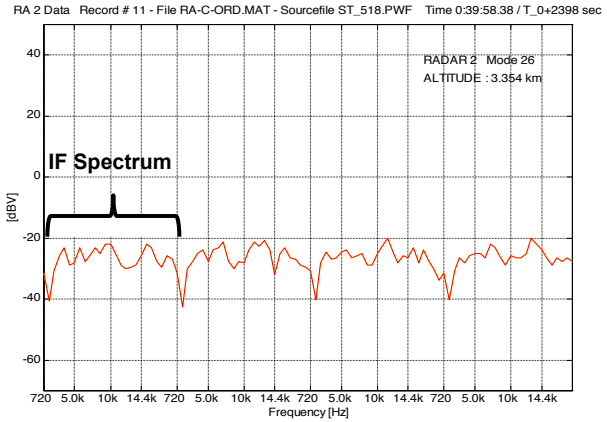
Atmospheric backscatter measurements (2)

Aerosol backscatter



Huygens data:





- 1/D signal visible: Z parameter and aerosol properties can be derived
- 1/D not visible: upper limits for Z can be derived

WISDOM Radar
Mission and Application

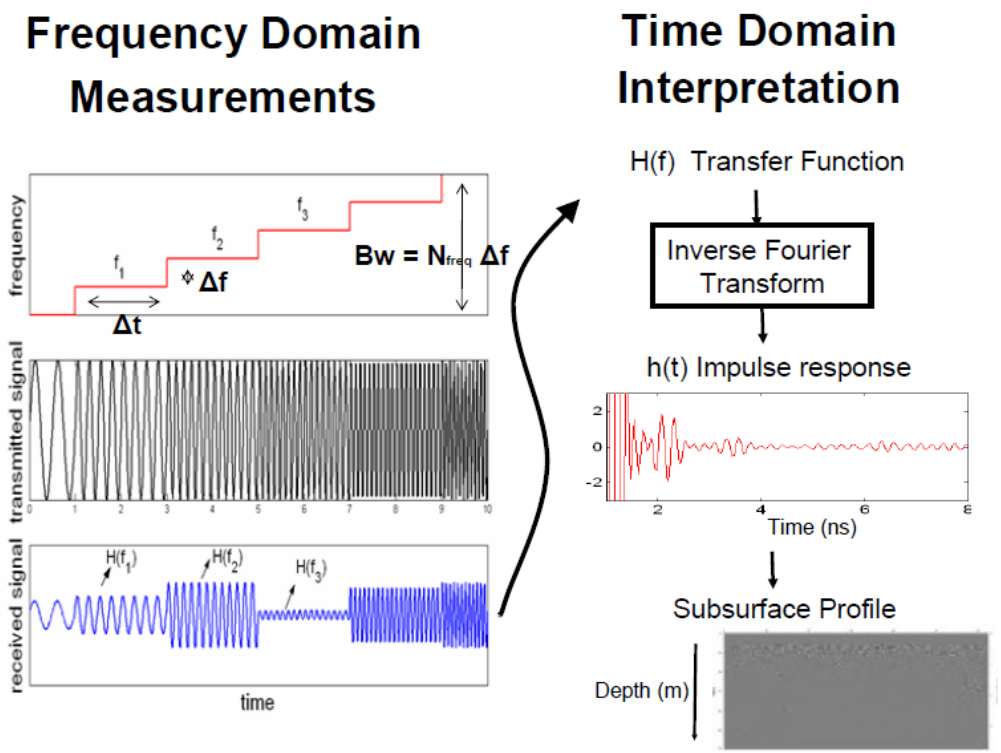
ExoMars Rover Mission

- Mars Exobiology rover
- Launch planned for 2018
- Sample retrieval from subsurface
- Analytical laboratory analysis
- Range of planetary science goals

Application

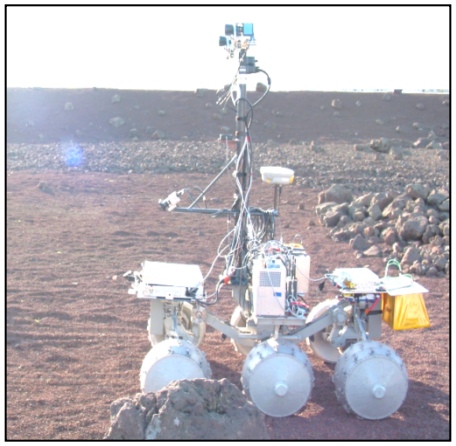
- Shallow subsurface investigations
- Detection of scatterers (rocks) and bedrock
- Detection of water / ice / interfaces
- Support to sample acquisition via drill

Step frequency radar – a flavour of FMCW



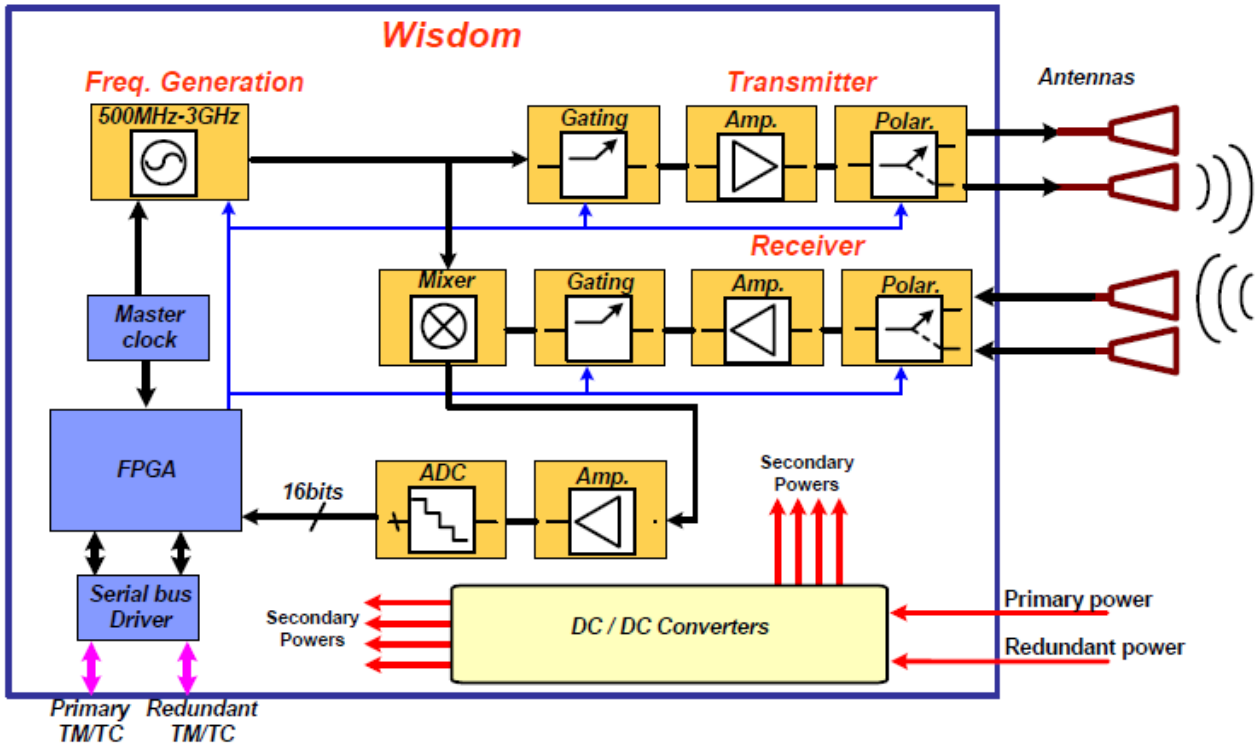
WISDOM key specs

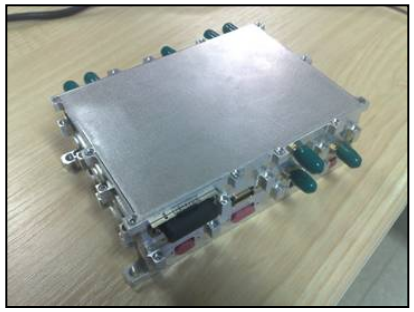
UHF Frequency	500 MHz – 3 GHz
Mass	~ 1.5 kg
Power	~ 11 Watts
RF power	10 – 20 dBm
Size box	~ 15 x 16 x 5 cm
Size antennas	~ 20 x 20 x 20 cm
Penetration depth	ca 3m
Resolution	few cm
Polarization	co & cross



Credits: V. Ciarletti / LATMOS/CNRS, France; D. Plettemeier / TU Dresden

Top level design / block diagram





WISDOM Electronics box

One antenna module

Credits: V. Ciarletti / LATMOS/CNRS, France; D. Plettemeier / TU Dresden

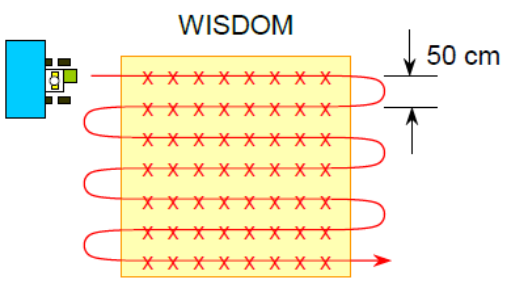
WISDOM Radar Operations & Science

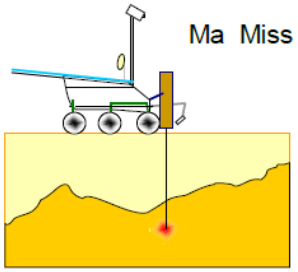
Science Objectives

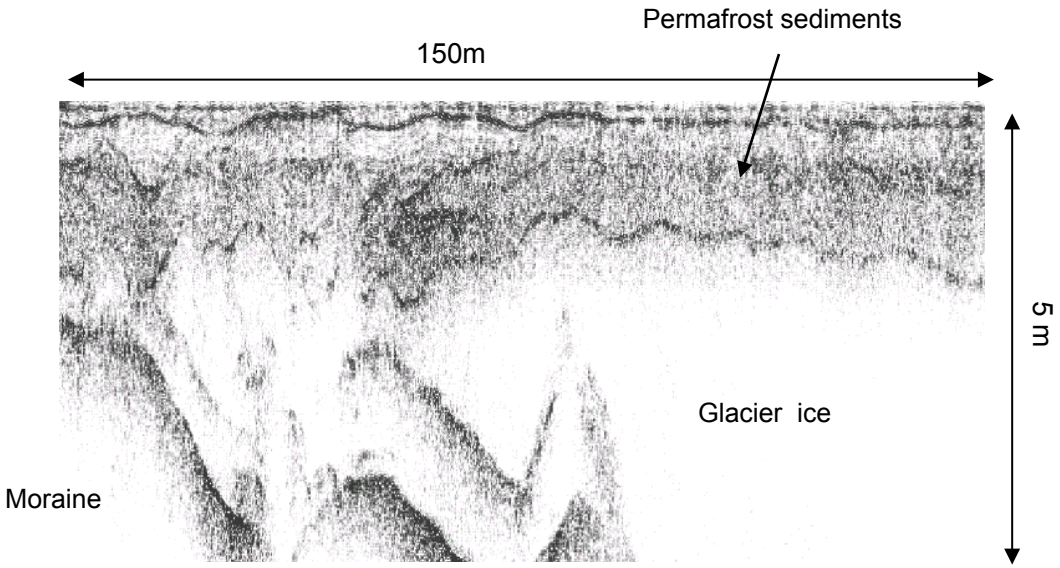
- Understand 3D geology and evolution of landing site
- Physical /compositional / electrical properties of subsurface
- Identify occurrences of water (solid / liquid)
- Identify most promising locations for drilling and sample acquisition by the drill system

Operations

- Soundings along rover track
- Scan pattern in area of scientific interest
- Individual soundings during the mission







Credits: V. Ciarletti / LATMOS/CNRS, France; D. Plettemeier / TU Dresden

Maturity & Future Evolution

Radars are a mature technology

- Successful implementations exist across the frequency range, for a diverse set of applications
- Gradual (not revolutionary) improvements to be expected wrt resource needs (mass, power, size) and performances (electronics, data processing, etc) and abilities
- Space applications are very specific and systems need to be tailored for their mission

Future radars in planetary exploration

- Based on heritage from successful missions; complementary to previous missions
- For exploration, new technologies are often adopted from Earth Observation and (sometimes) military or commercial areas, always adapted to specific mission needs
- Newer technologies generally allow larger choice of frequencies, lower noise RF systems, more sophisticated signal conditioning and processing
- Integration, performance, power efficiency of electronics is (~ slowly) improving
- More on-board data processing to be expected (to reduce data volumes)

Conclusions

- **A basic overview of radar types and their applications in space has been provided**

- **An small selection of radars flown on science & exploration missions was discussed**

Bottomline:

- **Radars are very powerful instruments!**
- **A range of functionalities can be provided, from passive sensing and simple altimetry to high resolution mapping and subsurface investigations**
- **Resource needs range from small to significant according to required functionality and performance**