Planetary Mapping From Earth: Applications of Radar

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Radar-bright Deposits near Mercury's North Pole

The highest-resolution radar image of Mercury’s north polar region made from the Arecibo Observatory (Harmon et al., Icarus, 211, 37-50, 2011) is shown in yellow on a mosaic of MESSENGER orbital images. Radar-bright features in the Arecibo image all collocate with areas mapped as in shadow in Mercury Dual Imaging System (MDIS) images to date, consistent with the proposal that radar-bright materials contain water ice. This image is shown in a polar stereographic projection with every 5° of latitude and 30° of longitude indicated and with 0° longitude at the bottom. On Mercury, 5° of latitude is approximately 213 km. Source: http://www.nasa.gov/mission_pages/messenger/multimedia/messenger_orbit_image20120322_3.html

Arecibo Observatory in Puerto Rico

http://www.playthewcc.com/things-to-do-in-san-juan

Overview

What is Radar?
  - Radar Basics
  - Theoretical Background
- Applications of Radar
  - Range–Doppler Mapping
  - Surface Roughness Estimation
  - Dielectric Constant Estimation

RADAR

- RADAR = RAdio Detection And Ranging
  - Uses electromagnetic waves to identify the range, altitude, direction, speed, roughness and electromagnetic properties of both moving and fixed objects such as aircraft, ships, motor vehicles, weather formations, and terrain.

http://www.srh.noaa.gov/jetstream/doppler/how.htm

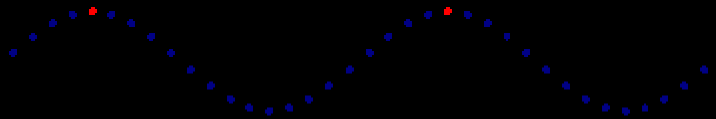
Planetary Mapping Applications

- Determining
  - Landscape
  - Chemical composition (dielectric constant)
  - Roughness (height variations, rms surface slope)
  - Other characteristics of planetary surfaces
    - Some locations are more ‘radar bright’ than others… Why?
- Can see through clouds (Venus)
  - Rotation period

Wavelength and Frequency

- Radar waves travel at the speed of light
- Wavelength, λ, is related to frequency, f, via

$$c = \lambda f$$

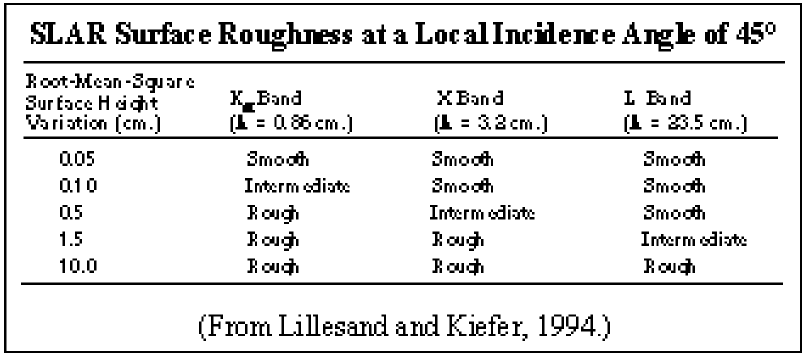


- Common Frequency Bands for Planetary Radar

Band name	Frequencies	Wavelengths
UHF	300 – 1000 MHz	0.3 – 1 m
S	2 – 4 GHz	7.5 – 15 cm
X	8 – 12 GHz	2.5 – 3.75 cm

Wavelength Matters

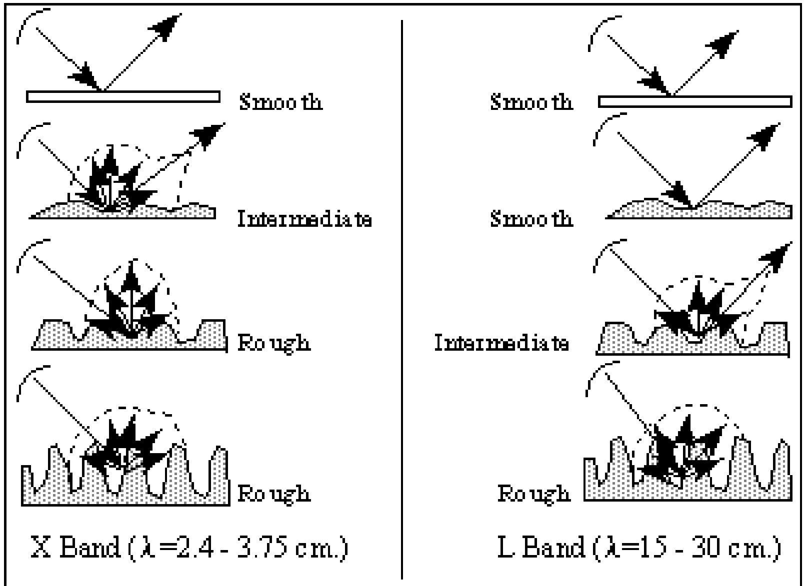
- Radar waves interact with surface features that are ‘*on the order of the wavelength or larger* ‘
  - The same surface responds differently to differently sized radar waves



SLAR Surface Roughness at a Local Incidence Angle of 45°

Root-Mean-Square Surface Height Variation (cm.)	K_a Band (λ = 0.86 cm.)	X Band (λ = 3.2 cm.)	L Band (λ = 23.5 cm.)
0.05	Smooth	Smooth	Smooth
0.10	Intermediate	Smooth	Smooth
0.5	Rough	Intermediate	Smooth
1.5	Rough	Rough	Intermediate
10.0	Rough	Rough	Rough

(From Lillesand and Kiefer, 1994.)

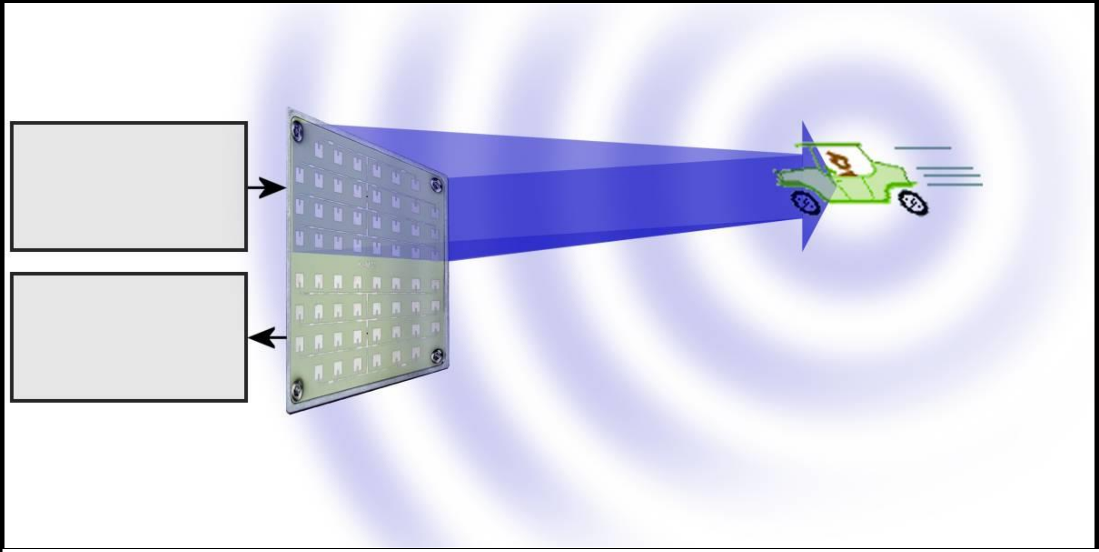


X-Band and L-Band radar reflection from surfaces of varying roughness. (After Lillesand and Kiefer, 1994.)

http://www.geo.hunter.cuny.edu/terrain/radariv.html

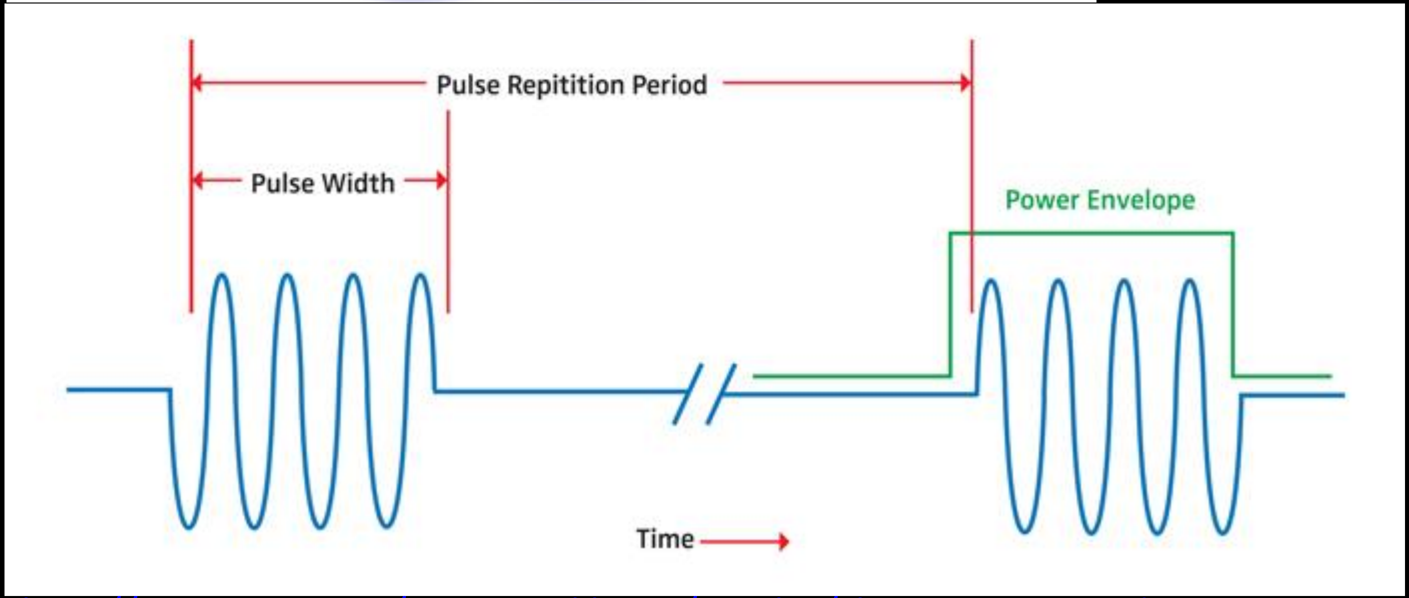
Continuous Wave vs. Pulses

CW



Need 2 antennas!

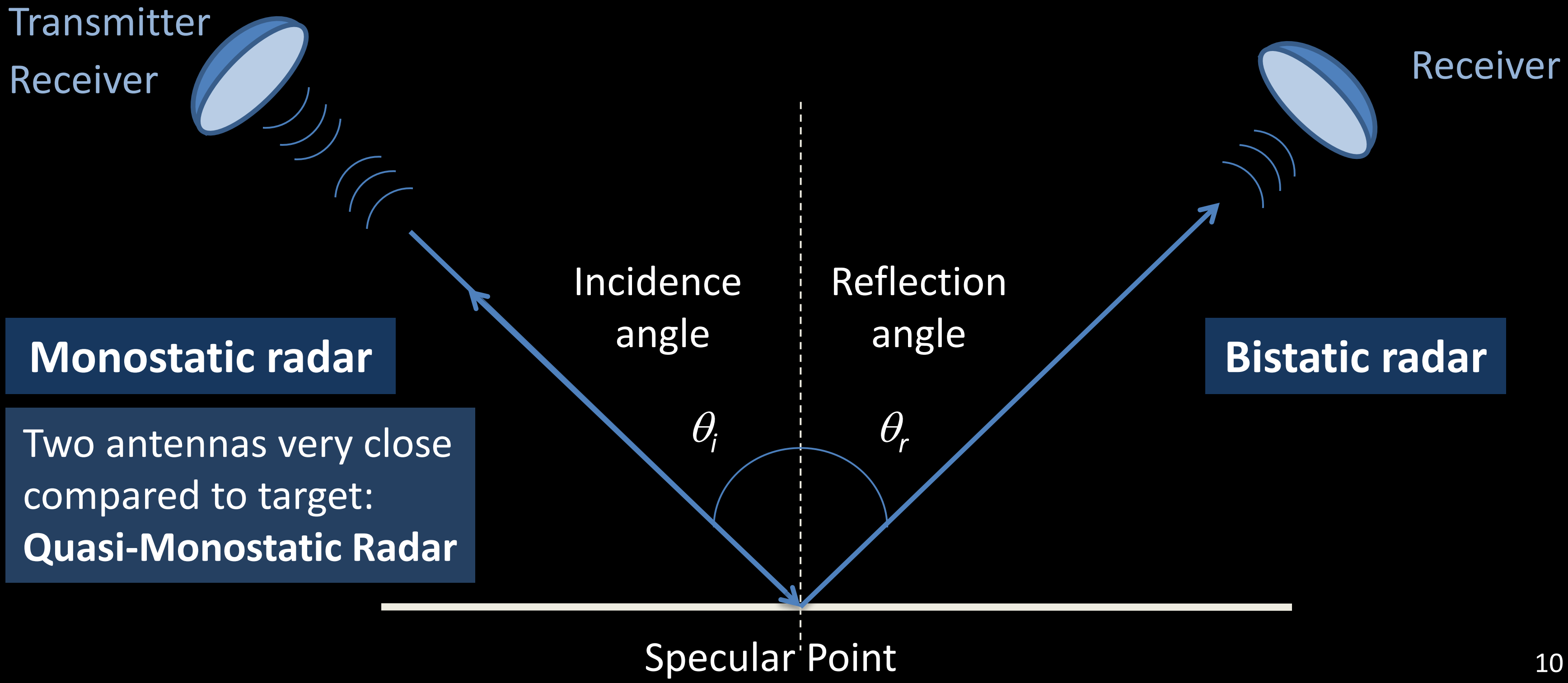
Pulses



http://noisecom.com/resource-library/articles/characterizing-radar

Radar Setups

- There are two main types of radar setups
  - Monostatic and Bistatic



Monostatic radar

Two antennas very close compared to target: **Quasi-Monostatic Radar**

Bistatic radar

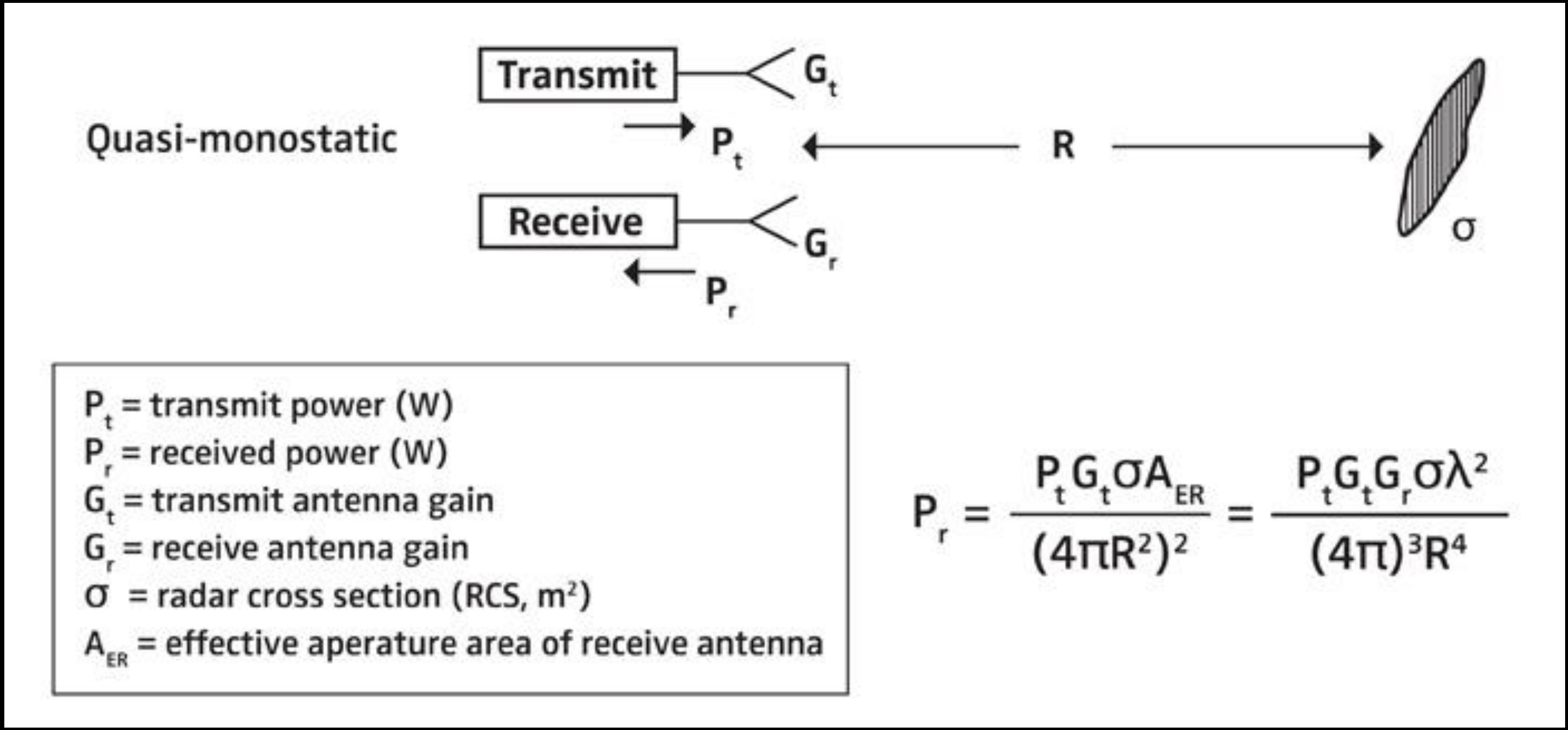
Radar Equation

- The received power scattered from a surface element *dS* is

$$dP_r = \underbrace{P_t\, G_t}_{\text{Power transmitted toward element}} \; \underbrace{\frac{1}{4\pi R_t^2}}_{\text{Propagation to element}} \; \underbrace{\sigma^o\, dS}_{\text{Radar Cross-Section (RCS)}} \; \underbrace{\frac{1}{4\pi R_r^2}}_{\text{Propagation to receiver}} \; \underbrace{\frac{\lambda^2\, G_r}{4\pi}}_{\text{Effective receiver aperture}}$$

- The Radar Cross Section
  - indicates how well the surface element reflects power towards the receiver
  - is a function of incidence and reflection geometry and surface properties

Radar Equation (Monostatic)

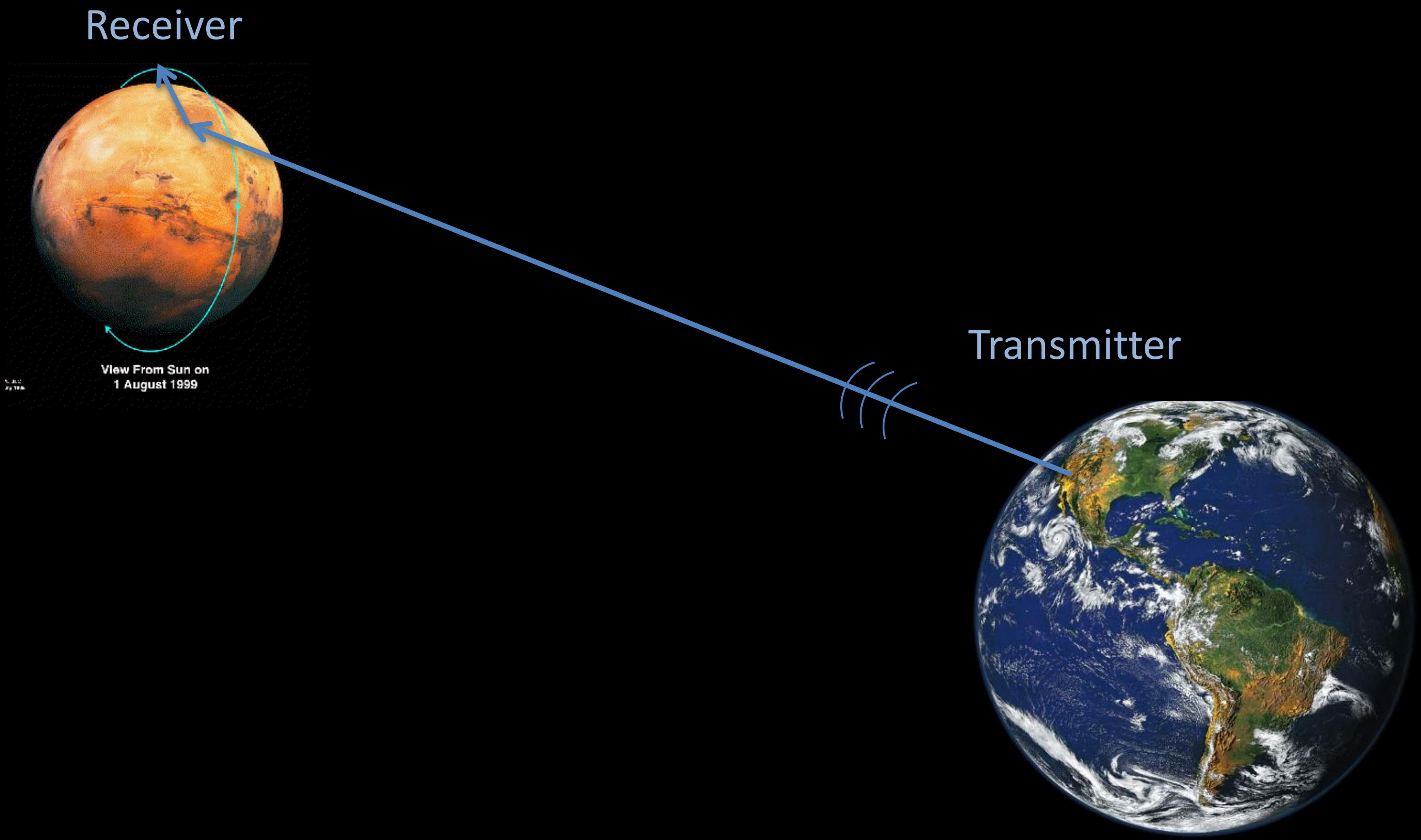


P_t = transmit power (W)
P_r = received power (W)
G_t = transmit antenna gain
G_r = receive antenna gain
σ = radar cross section (RCS, m^2)
A_{ER} = effective aperature area of receive antenna

$$P_r = \frac{P_t G_t \sigma A_{ER}}{(4\pi R^2)^2} = \frac{P_t G_t G_r \sigma \lambda^2}{(4\pi)^3 R^4}$$

http://noisecom.com/resource-library/articles/characterizing-radar

Planetary Bistatic Radar



Receiver

Transmitter

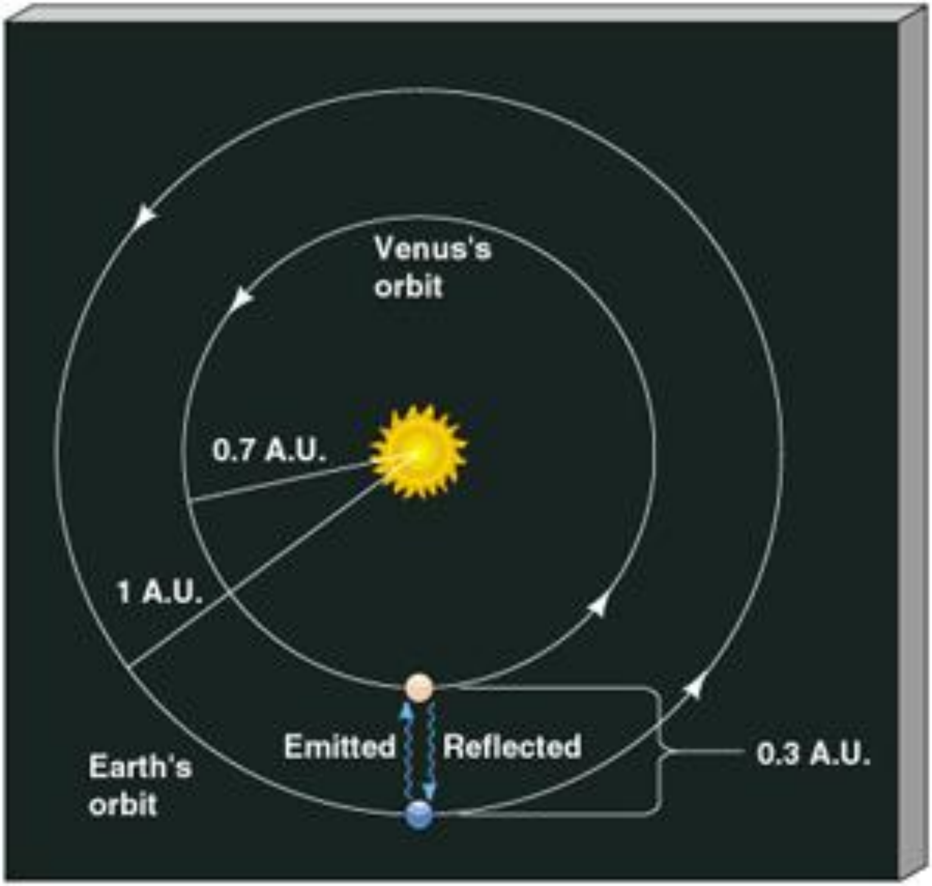
Trade-offs

- Bistatic vs. Earth-based monostatic radar
  - Increased received signal power due to one-way interplanetary travel
  - The specular point is localized and traverses the planet with the spacecraft

- Uplink vs. Downlink
  - Earth-based transmitters are much more powerful
  - Spacecraft receivers are inferior to Earth-based ones

Orbital Considerations

- The planets move!!



http://www.castlerock.wednet.edu/HS/stello/Astronomy/TEXT/CHAISSON/BG301/HTML/BG30103.htm

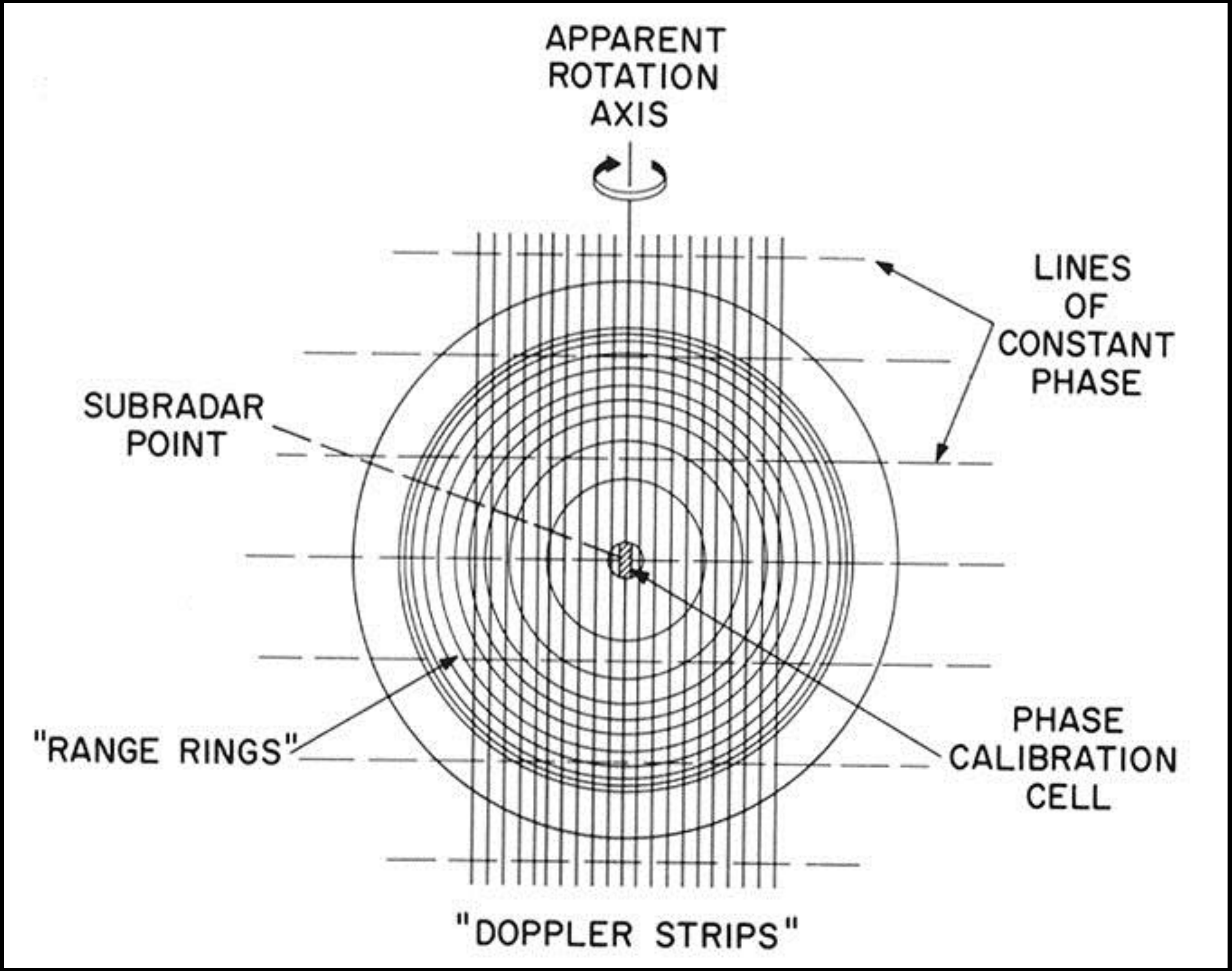
Application:

Range – Doppler Mapping

(Monostatic or Quasi-Monostatic)

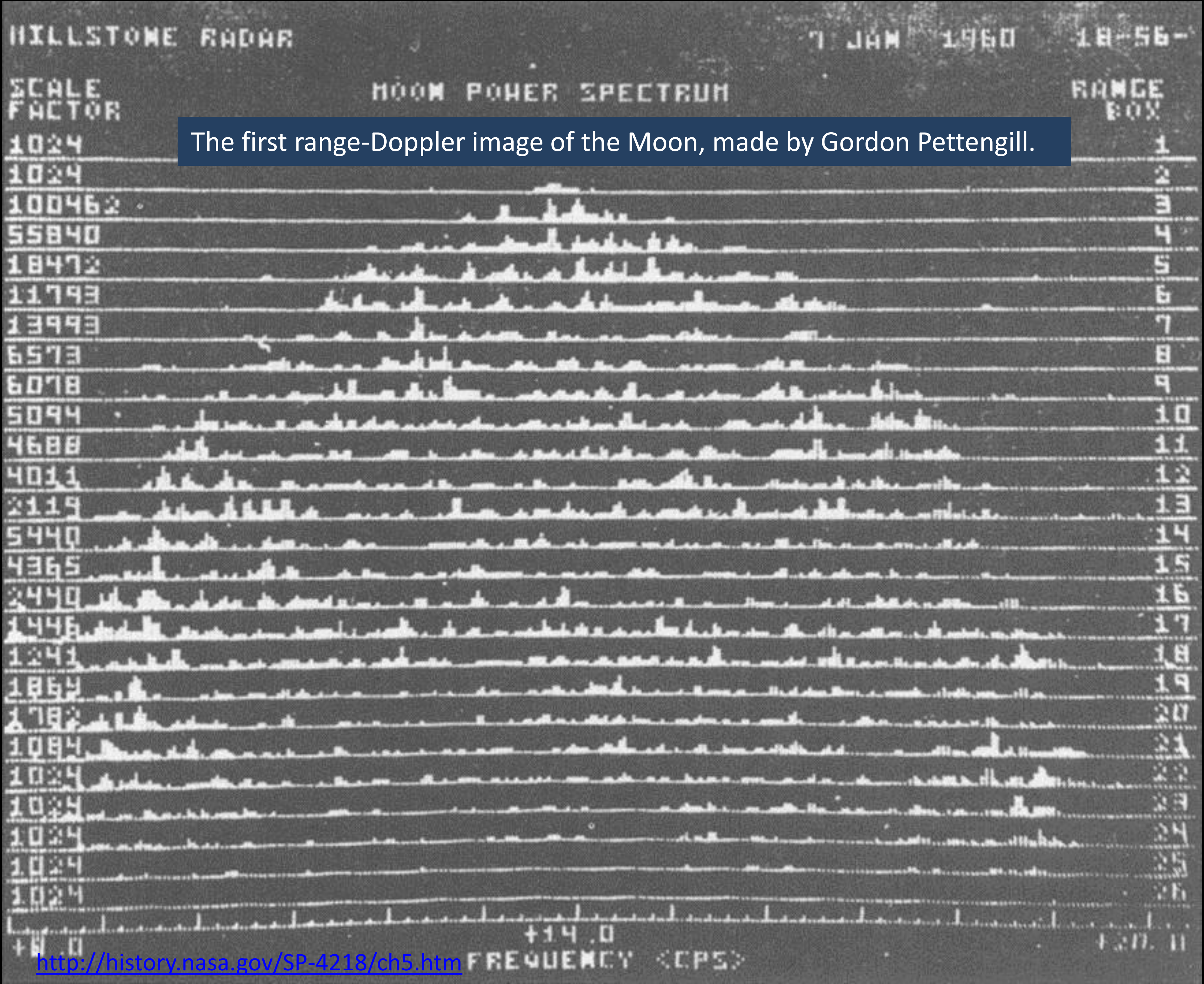
Range-Doppler Maps

- Where does the radar echo come from?



Note:
North-South
Ambiguity!

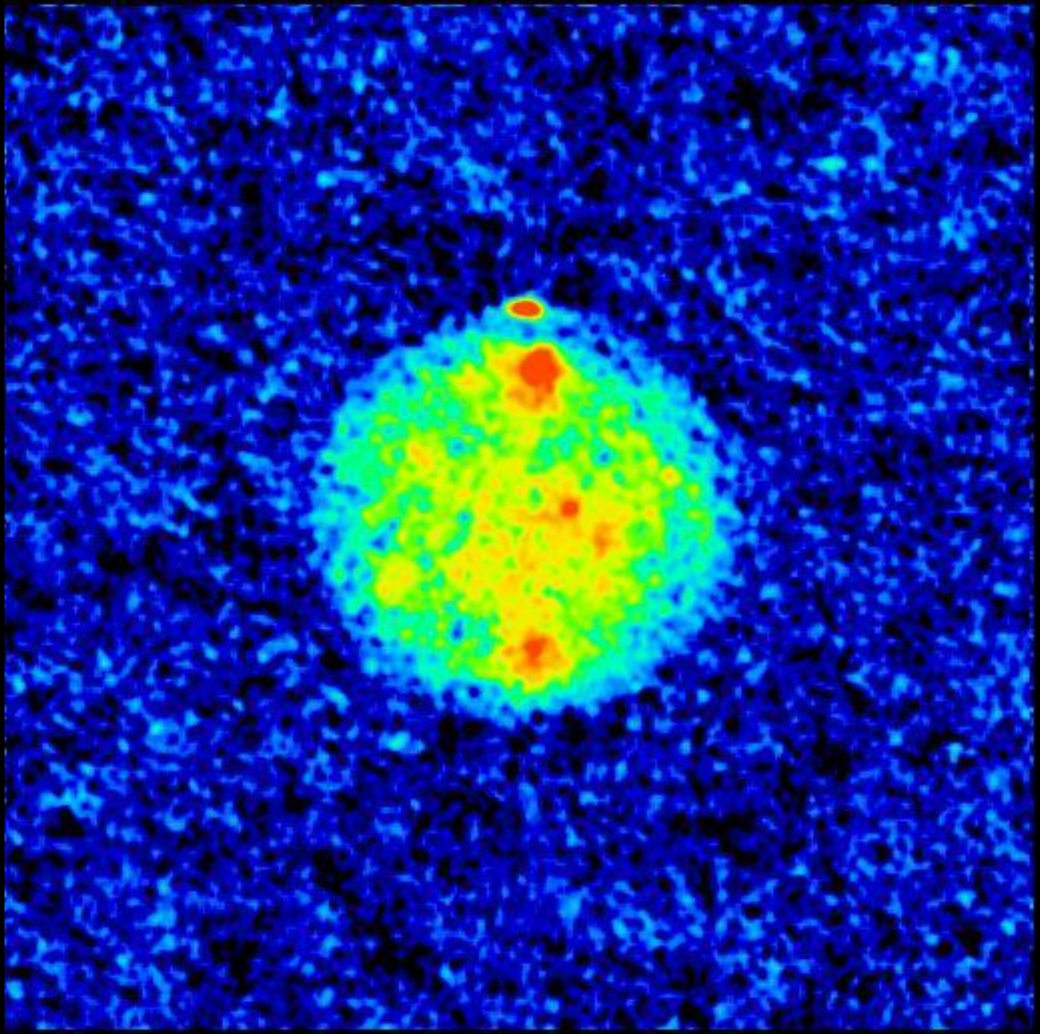
http://history.nasa.gov/SP-4218/essay.htm



The first range-Doppler image of the Moon, made by Gordon Pettengill.

http://history.nasa.gov/SP-4218/ch5.htm

Mercury Map (Goldstone/VLA 1991)



- Radio waves were transmitted to **Mercury** and some reflected off the planet and returned to Earth, where they were detected by radio telescopes.
- Red areas show regions of highest reflectivity, that is, where more radio waves reflected back to Earth.
- The northern red spot is due to water-ice resting in permanent shade on Mercury's pole.
- The origin of the other red (highly reflective) areas remain a mystery.

http://www.gb.nrao.edu/epo/sol_sys/rmercury.html

Goldstone and the VLA

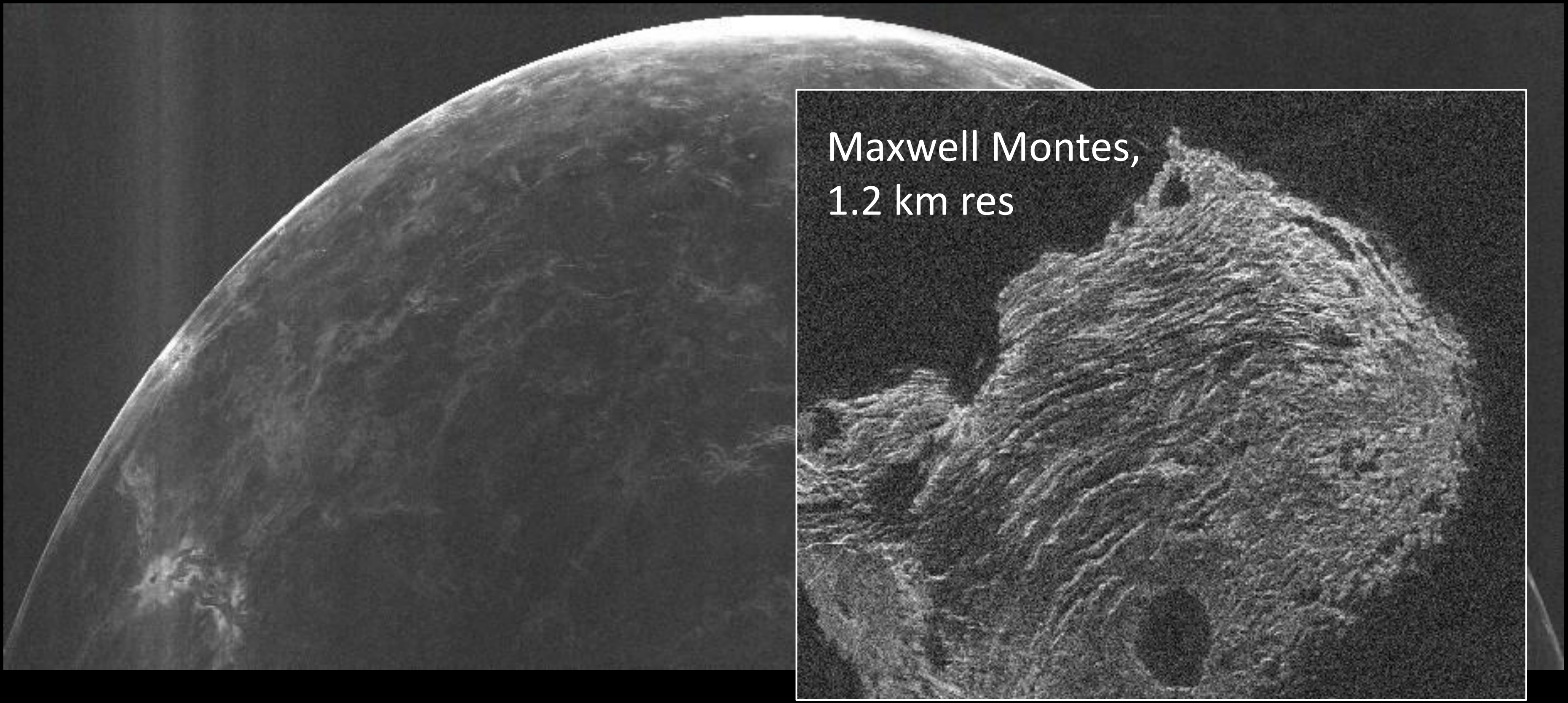
http://www.nrao.edu/archives/Timeline/VLA-D_lo.shtml

The NROA Very Large Array, a collection of 27 x 25-m antennas in New Mexico, USA.

70-m Deep Space Network antenna at Goldstone, California, USA.

http://deepspace.jpl.nasa.gov/dsn/gallery/goldstone3.html

Venus

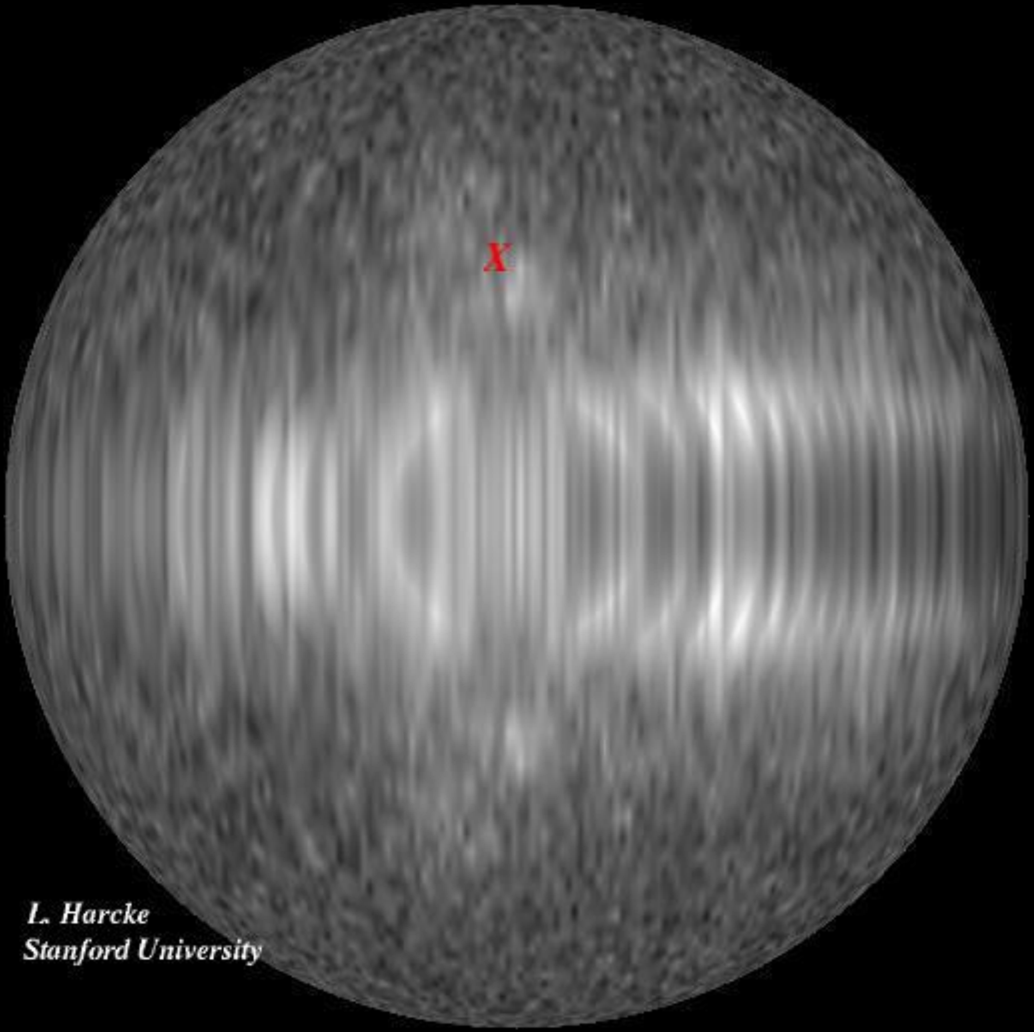


Delay-Doppler images were obtained by transmitting continuously from Arecibo Observatory and receiving the radar echoes at the 100 meter Green Bank Telescope in 2001 (5 km resolution, D. Campbell et al.) http://www.naic.edu/~pradar/pradar.htm

100 m Green Bank Telescope

http://www.nsf.gov/news/news_images.jsp?cntn_id=117366&org=NSF

Jupiter’s Satellite Callisto



This image is a radar albedo map of the western hemisphere of Callisto.

An ambiguity exists between the northern and southern halves of the planet due to the range-Doppler imaging technique employed, thus the image appears symmetric about the equator.

A projection effect causes the resolution cells to be long and thin nearer to the equator. Signal to noise ratio is strongest near the sub-Radar point.

http://www.naic.edu/general/index.php?option=com_content&view=article&id=146&Itemid=474

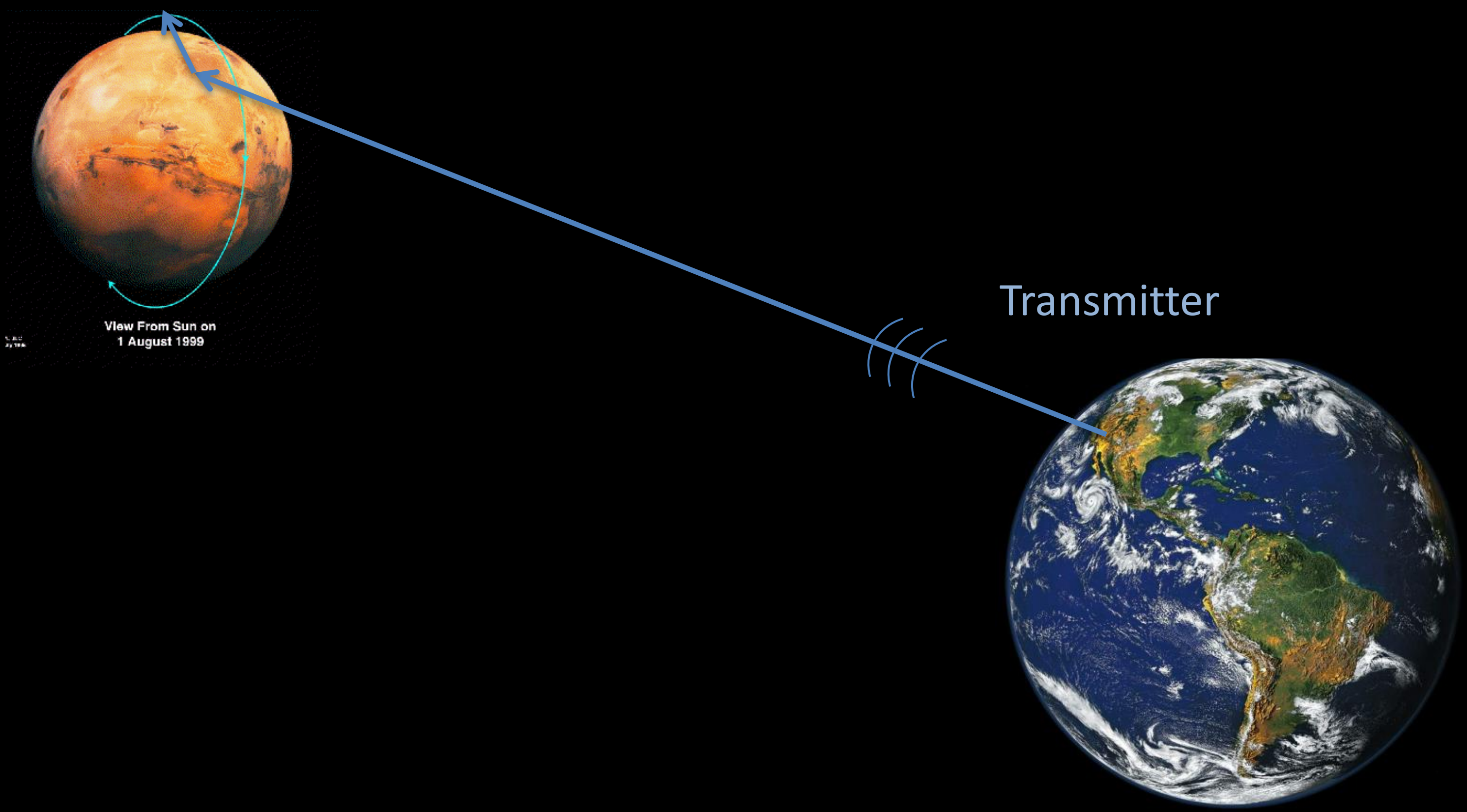
Range – Doppler Limitations

- Only works well for ‘slowly’ rotating bodies
  - Mercury, Venus, the Moon…
  - Mars spins too fast, is ‘overspread’ (blurry)
  - North-South ambiguity if too far away to aim
  - Signal strength less because of two-way travel

Application:

Surface Roughness via Bistatic Radar

Planetary Bistatic Radar - Uplink



Receiver

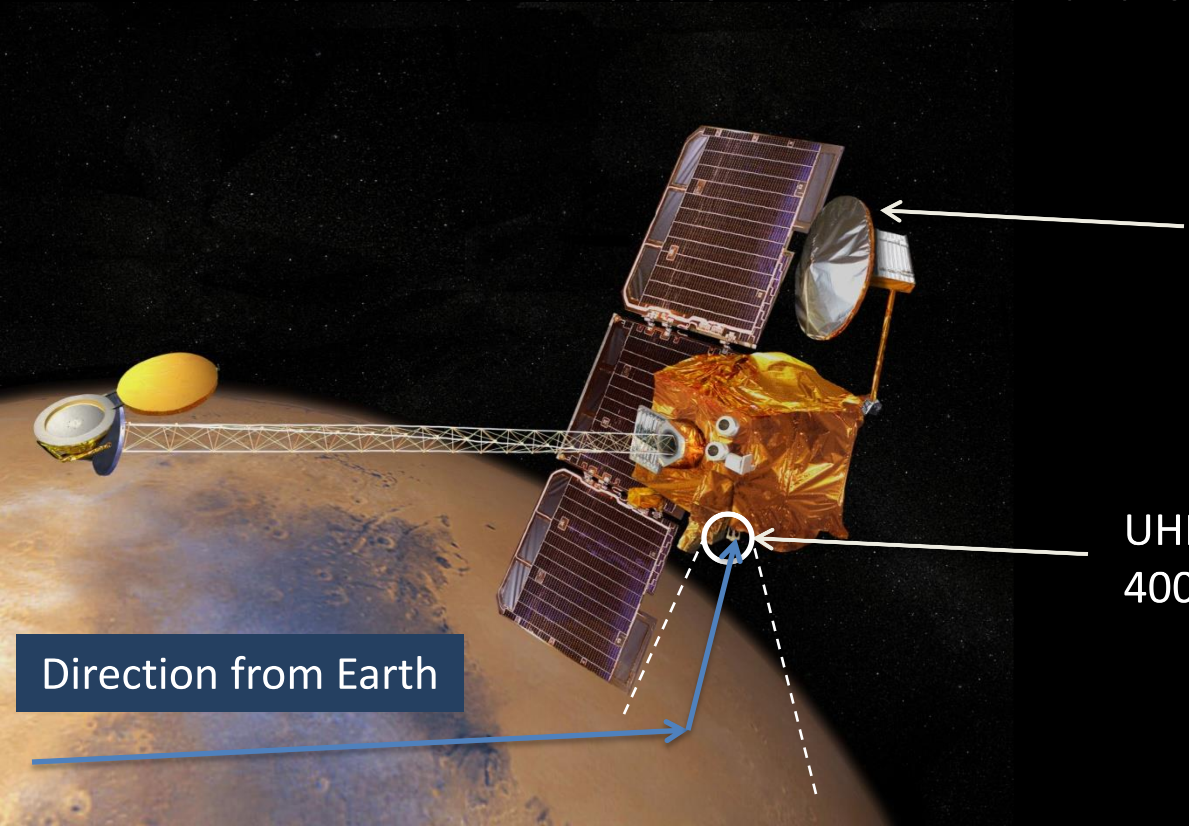
Transmitter

Transmitter: The SRI 46-m Antenna

- Constructed in the early 1960s
- The 46-m aperture with 30 kW transmitter power produces the highest full sky pointing targeted EIRP (effective isotropic radiated power) at UHF frequencies in the world

Receiver: Mars Odyssey

- The Mars Odyssey spacecraft was launched on April 7th, 2001.
- The orbiter functions as a communications relay between landers on the surface of Mars and the Earth.
- The UHF antenna has a 37° beam-width and is pointed 17° off nadir.

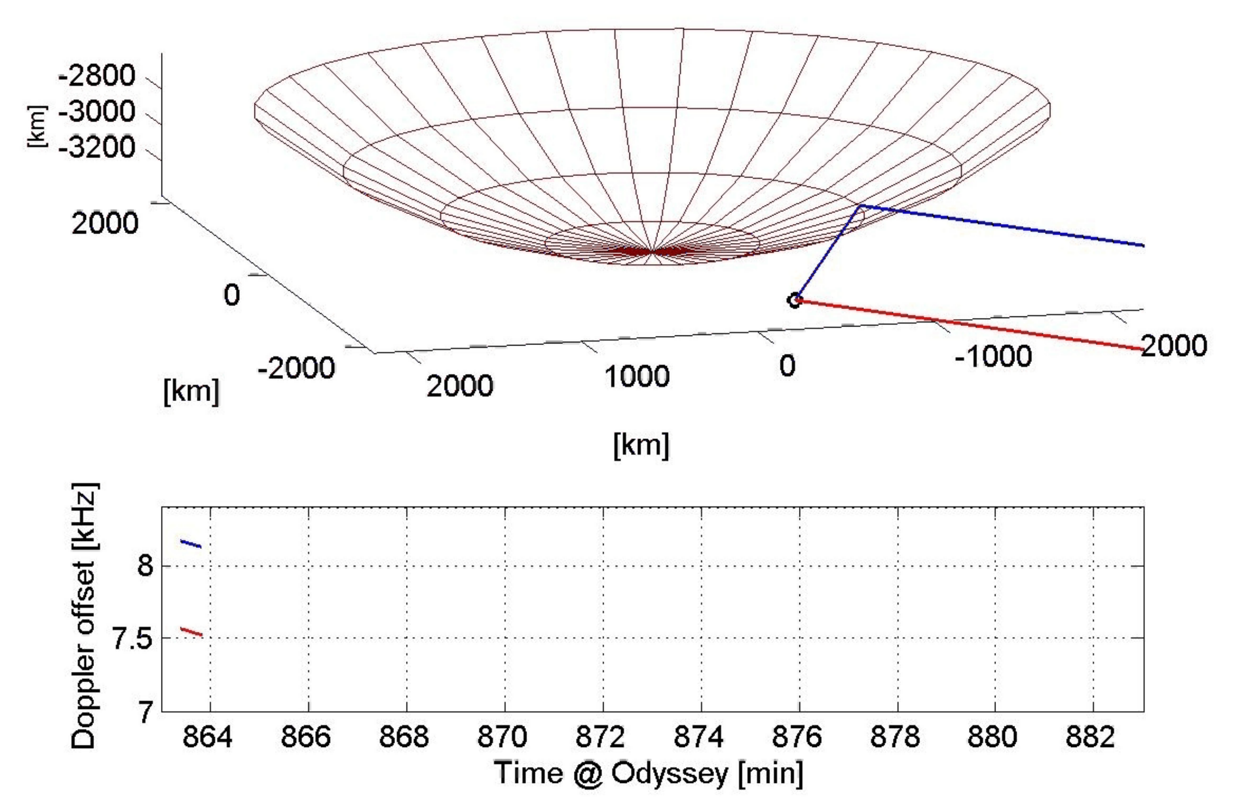


High Gain Antenna
X-band

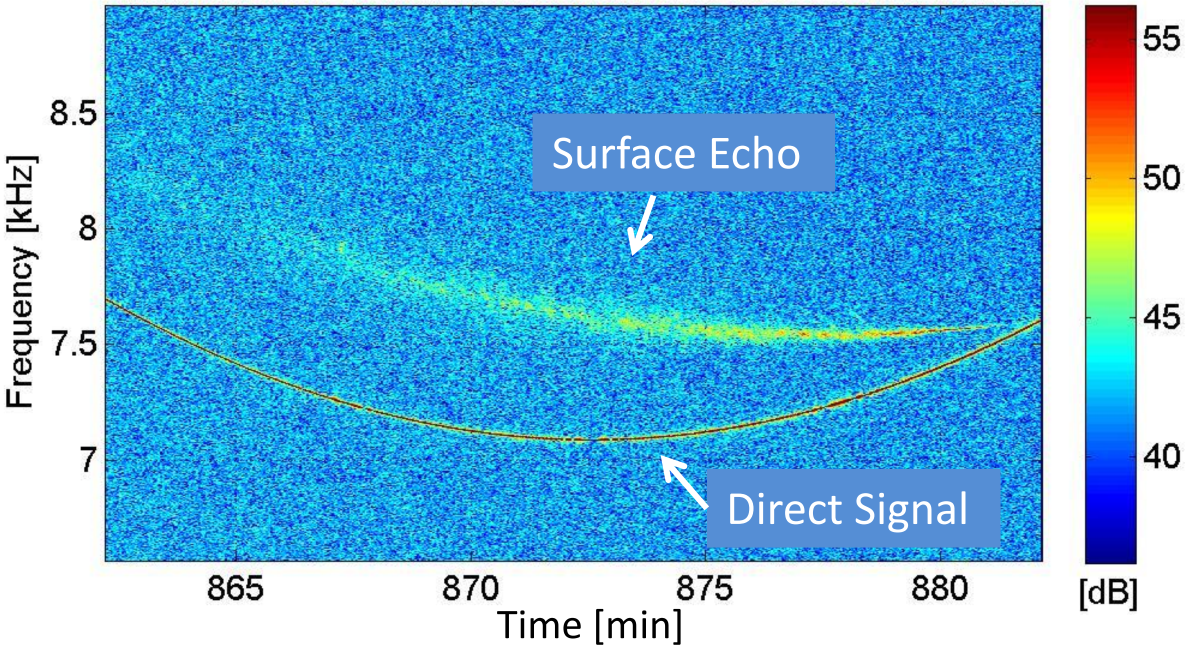
UHF antenna
400 MHz (75 cm)

Direction from Earth

Bistatic Geometry

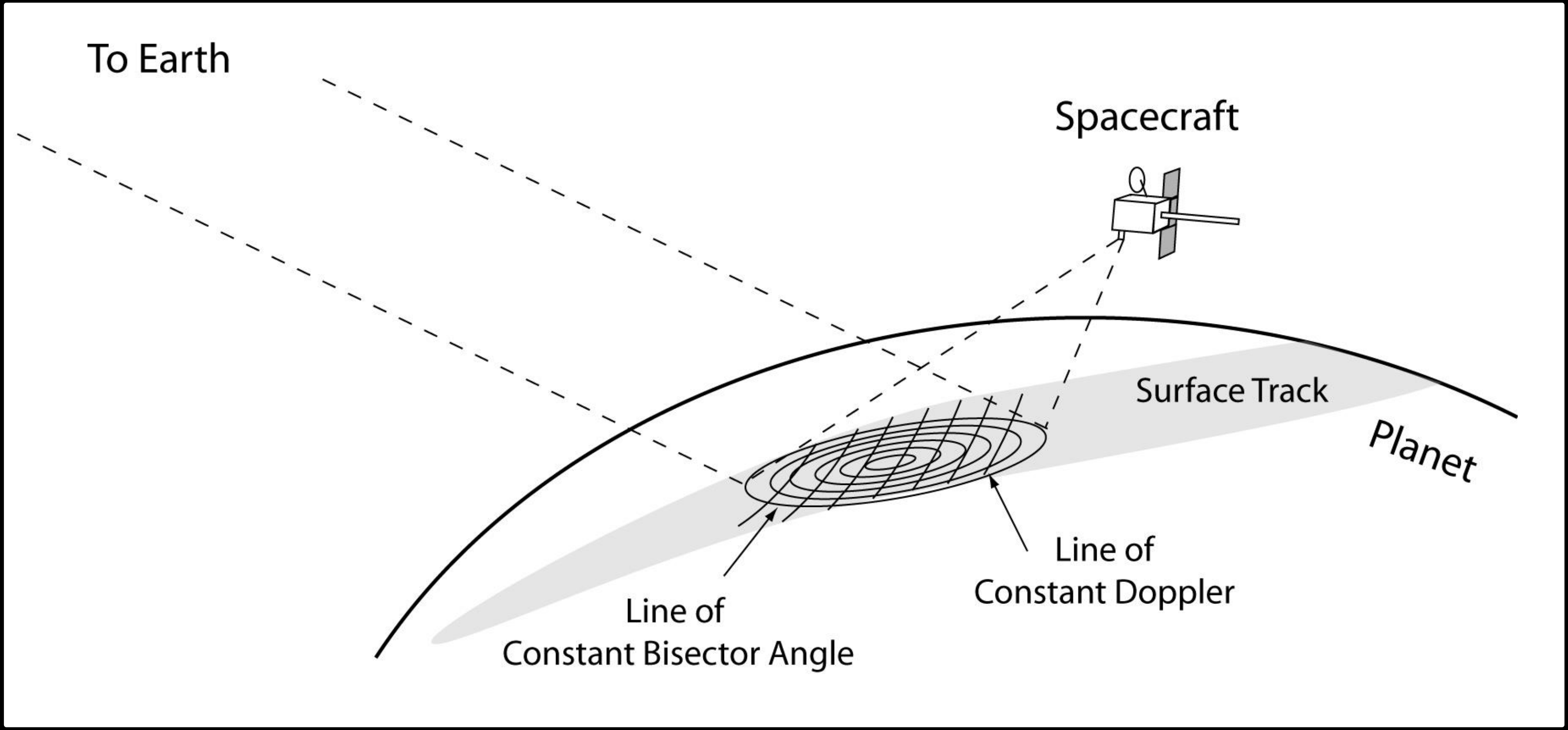


Data - Spectrogram



Surface Mapping

- The surface is mapped in two dimensions



Surface Model Extraction

- The radar equation

$$dP_r = P_t G_t \frac{1}{4\pi R_t^2} \sigma^o dS \frac{1}{4\pi R_r^2} \frac{\lambda^2 G_r}{4\pi}$$

- Each surface element *dS* has a Doppler frequency *f* and bisector angle θ_b
- We want to solve

$$\mathbf{P}_r(f) = \mathbf{K}(f, \theta_b)\boldsymbol{\sigma}^o(\theta_b)$$

Echo Spectrum

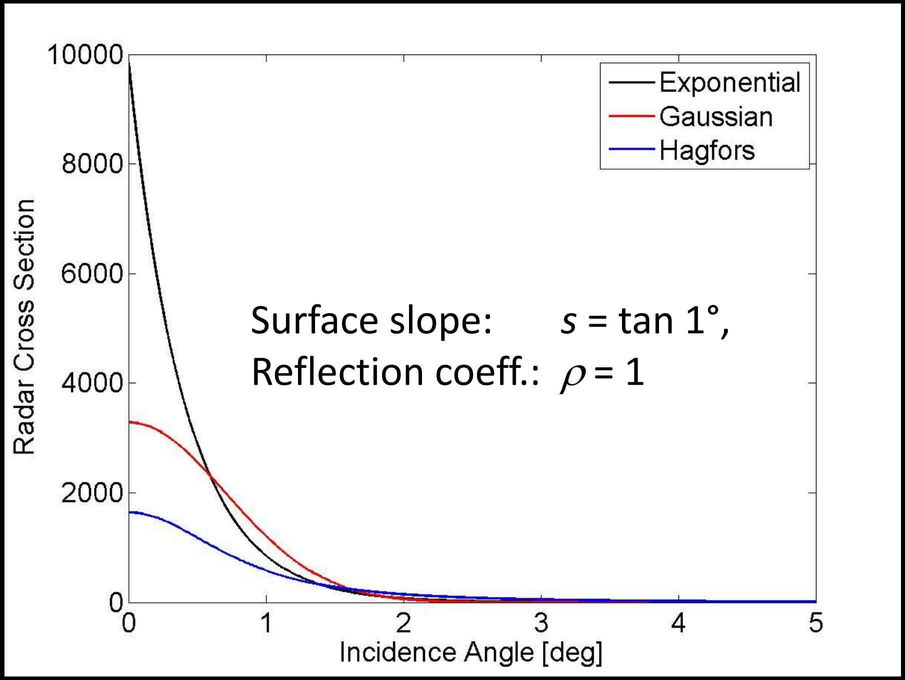
Geometric & antenna factors

Scattering model

Radar Cross Section Models

(aka Scattering Models)

- Multiple scattering models have been proposed
- Common: Reflectivity x Shape due to roughness



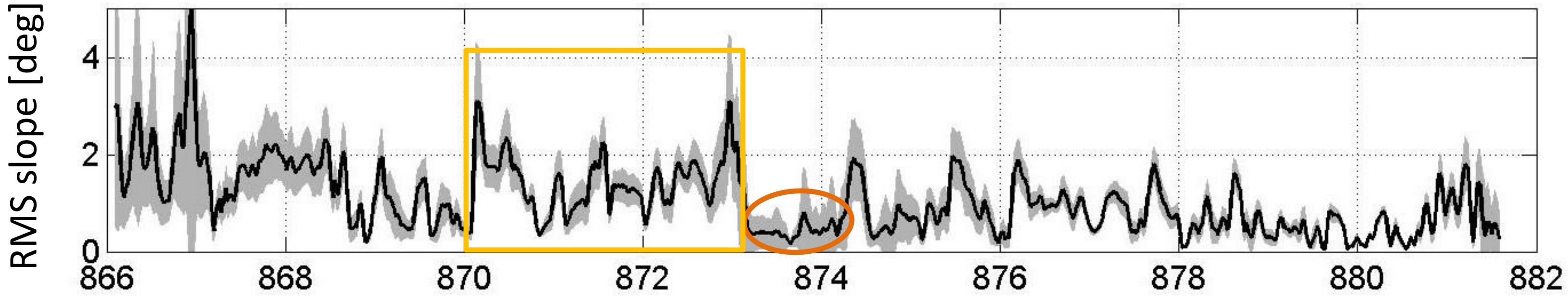
Surface slope: $s = \tan 1°$,
Reflection coeff.: $\rho = 1$

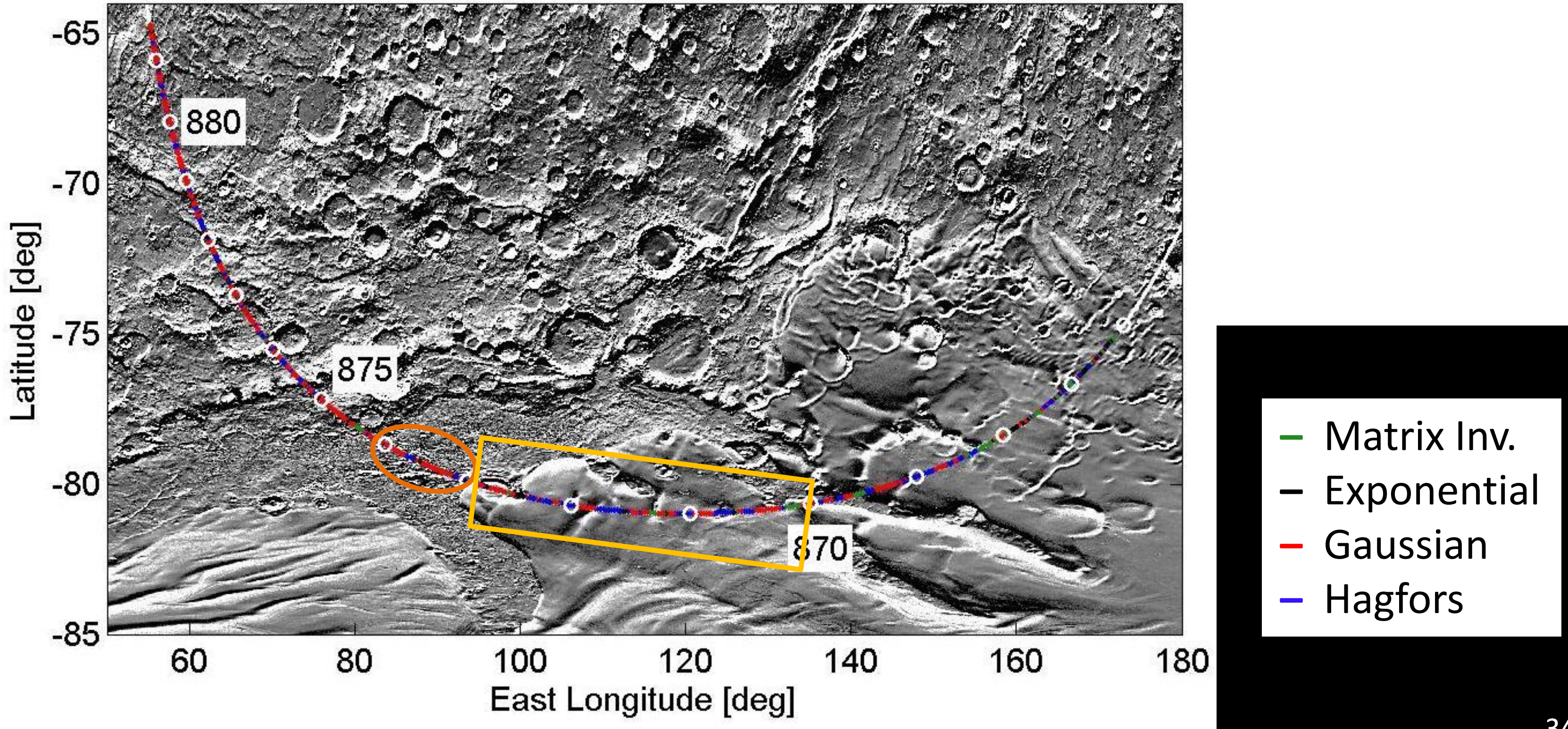
$$\sigma_E^o = \frac{3\rho}{s^2 \cos^4 \theta_i} \exp\left(-\frac{\sqrt{6}\tan\theta_i}{s} \right)$$

$$\sigma_G^o = \frac{\rho}{s^2 \cos^4 \theta_i} \exp\left(-\frac{\tan^2\theta_i}{s^2} \right)$$

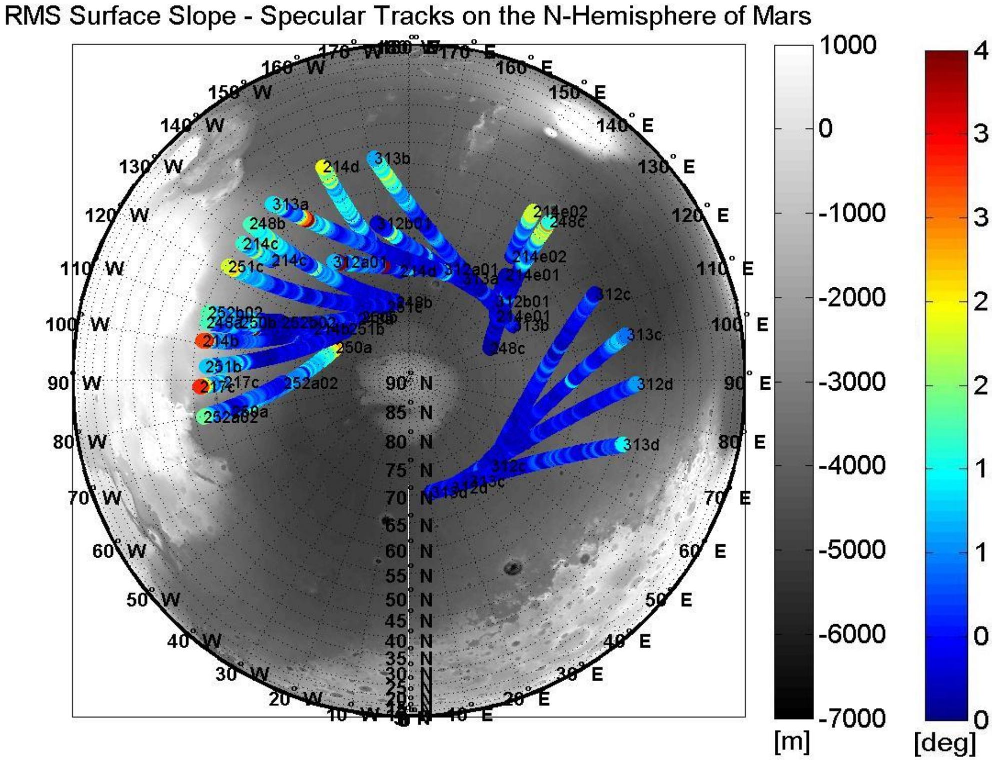
$$\sigma_H^o = \frac{\rho}{2s^2} \left(\cos^4 \theta_i + \frac{1}{s^2} \sin^2 \theta_i \right)^{-3/2}$$

RMS Surface Slope in Context

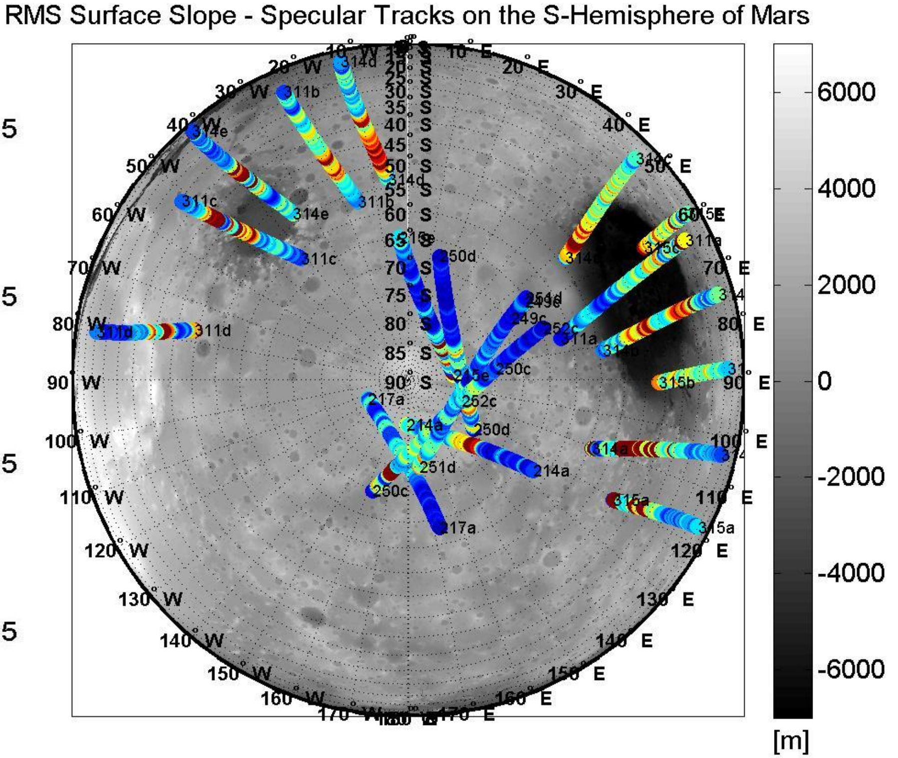




RMS Surface Slope Maps



RMS Surface Slope - Specular Tracks on the N-Hemisphere of Mars



RMS Surface Slope - Specular Tracks on the S-Hemisphere of Mars

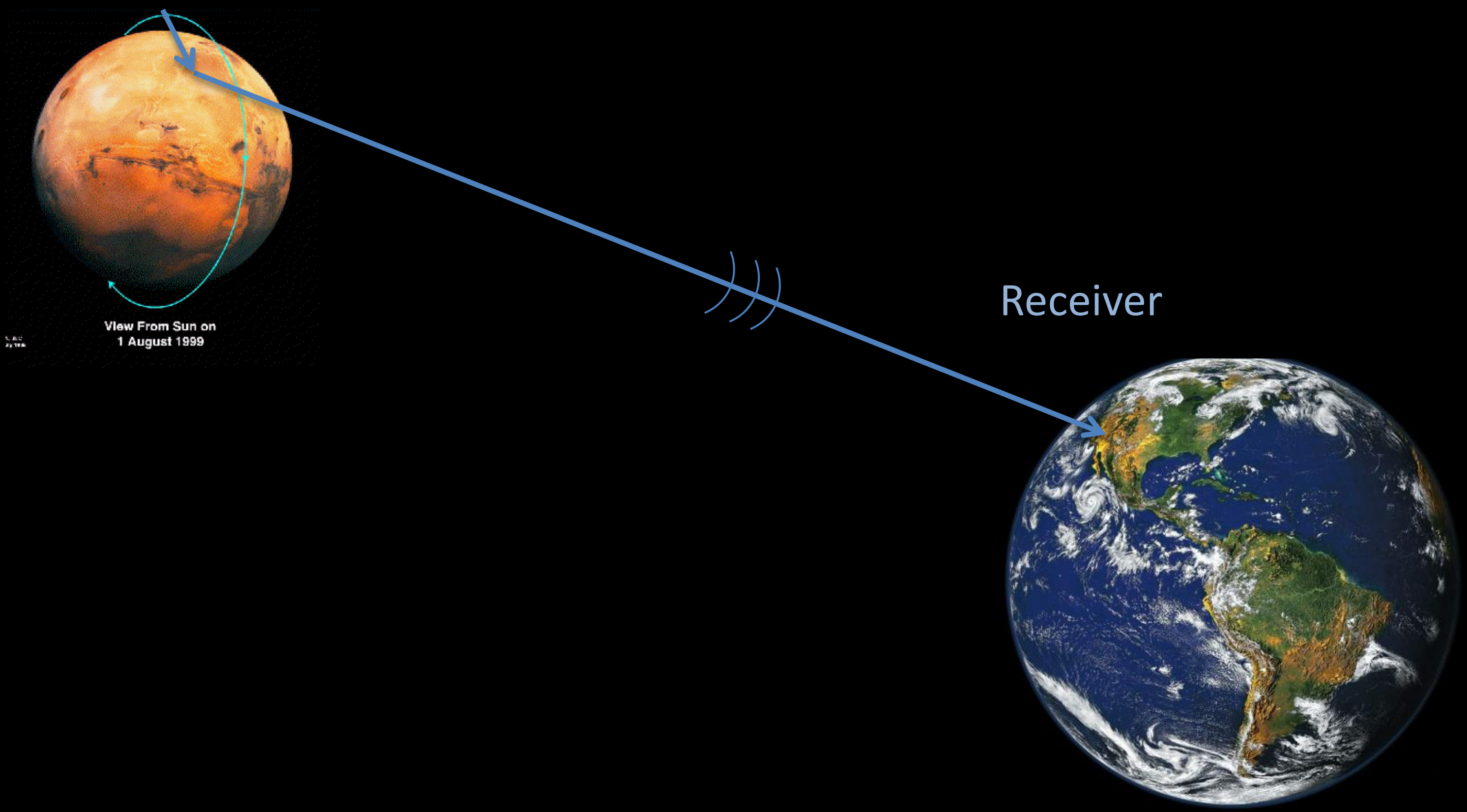
Pros and Cons

- Pros
  - Target areas out of bounds for Earth-based monostatic radars
  - Relatively cheap experiment (piggy-backing)
- Cons
  - Low resolution
  - Spacecraft receiver non-optimal

Application:

Dielectric Constant Estimation via Bistatic Radar

Planetary Bistatic Radar - Downlink

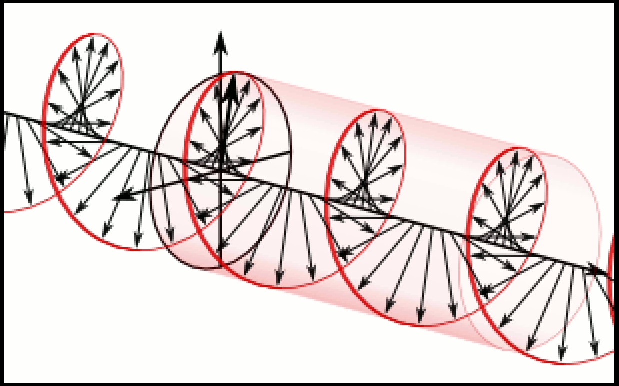


Transmitter

Receiver

Polarization

- Electromagnetic waves are polarized
  - Vertical/Horizontal, Right/Left Circular, Elliptical



- Need to capture echoes in two polarizations for full characterization

http://en.wikipedia.org/wiki/Circular_polarization

Surface Echoes in Two Polarizations

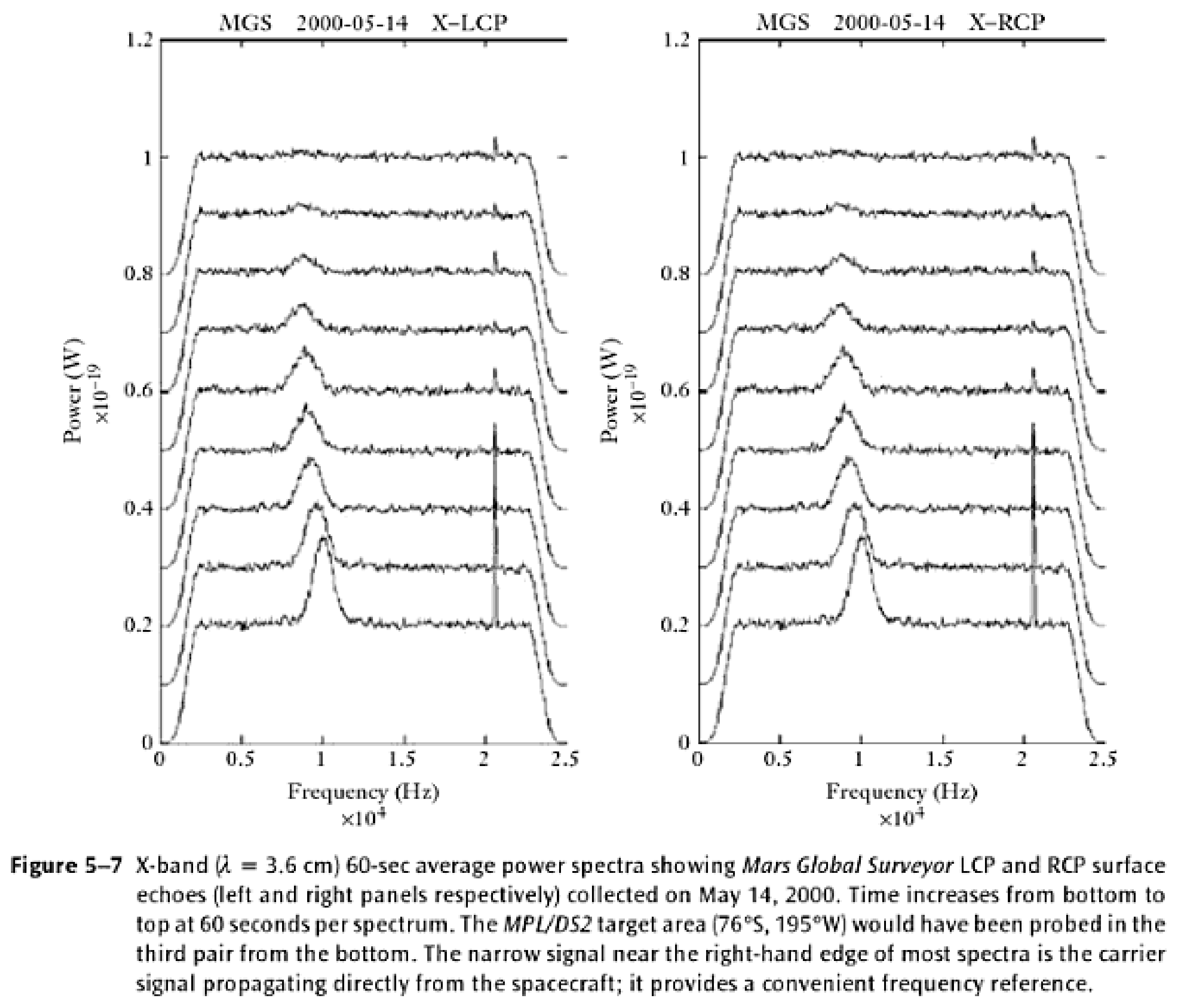
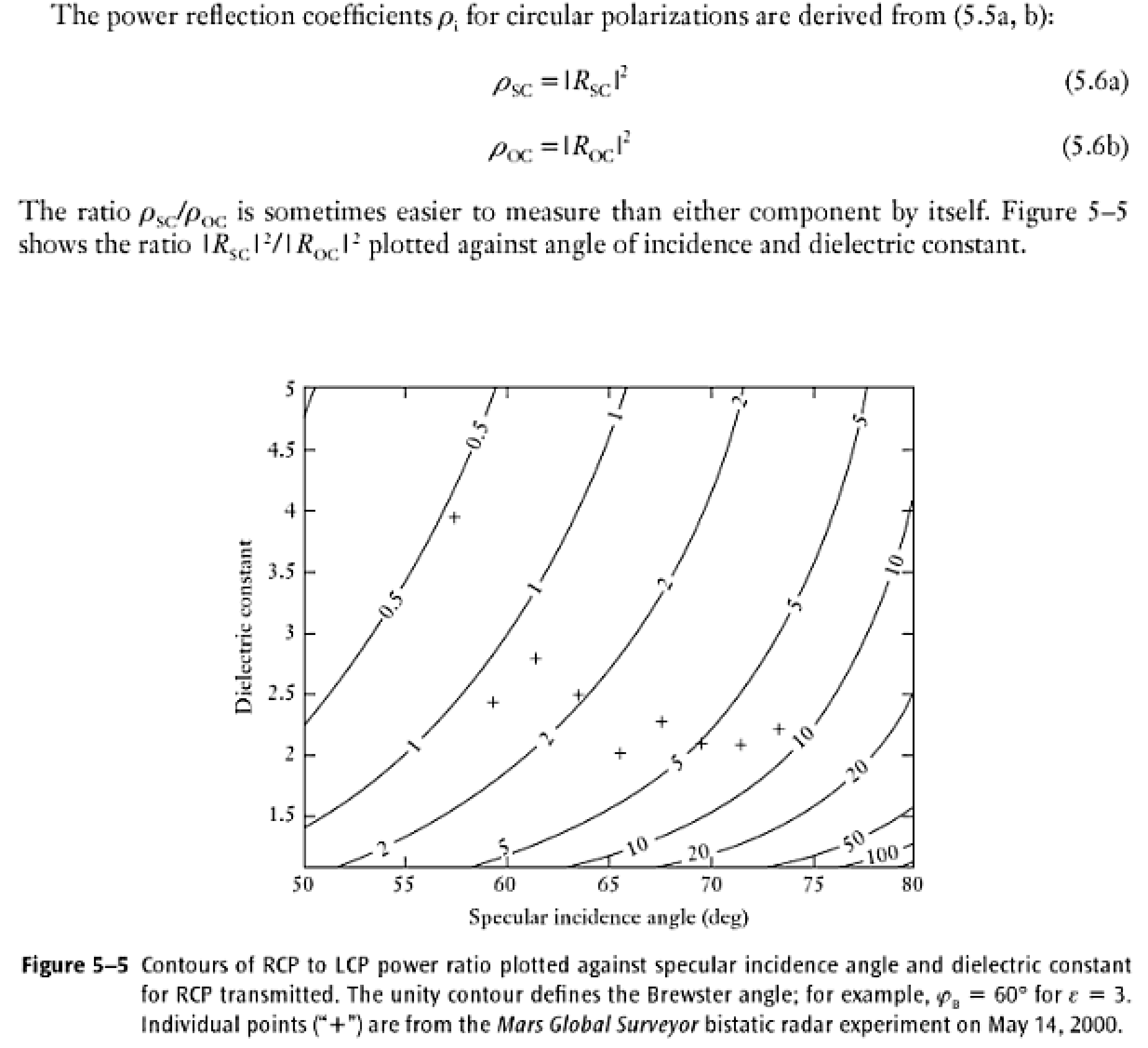


Figure 5–7 X-band (λ = 3.6 cm) 60-sec average power spectra showing *Mars Global Surveyor* LCP and RCP surface echoes (left and right panels respectively) collected on May 14, 2000. Time increases from bottom to top at 60 seconds per spectrum. The *MPL/DS2* target area (76°S, 195°W) would have been probed in the third pair from the bottom. The narrow signal near the right-hand edge of most spectra is the carrier signal propagating directly from the spacecraft; it provides a convenient frequency reference.

From **Advances in Bistatic Radar** edited by Willis and Griffiths. Work by Simpson.

Reflection Coefficient Estimate



The power reflection coefficients ρ_i for circular polarizations are derived from (5.5a, b):

$$\rho_{SC} = |R_{SC}|^2 \tag{5.6a}$$

$$\rho_{OC} = |R_{OC}|^2 \tag{5.6b}$$

The ratio ρ_{SC}/ρ_{OC} is sometimes easier to measure than either component by itself. Figure 5–5 shows the ratio $|R_{SC}|^2/|R_{OC}|^2$ plotted against angle of incidence and dielectric constant.

Figure 5–5 Contours of RCP to LCP power ratio plotted against specular incidence angle and dielectric constant for RCP transmitted. The unity contour defines the Brewster angle; for example, $\varphi_B = 60°$ for $\varepsilon = 3$. Individual points ("+") are from the *Mars Global Surveyor* bistatic radar experiment on May 14, 2000.

Dielectric Constant of Materials

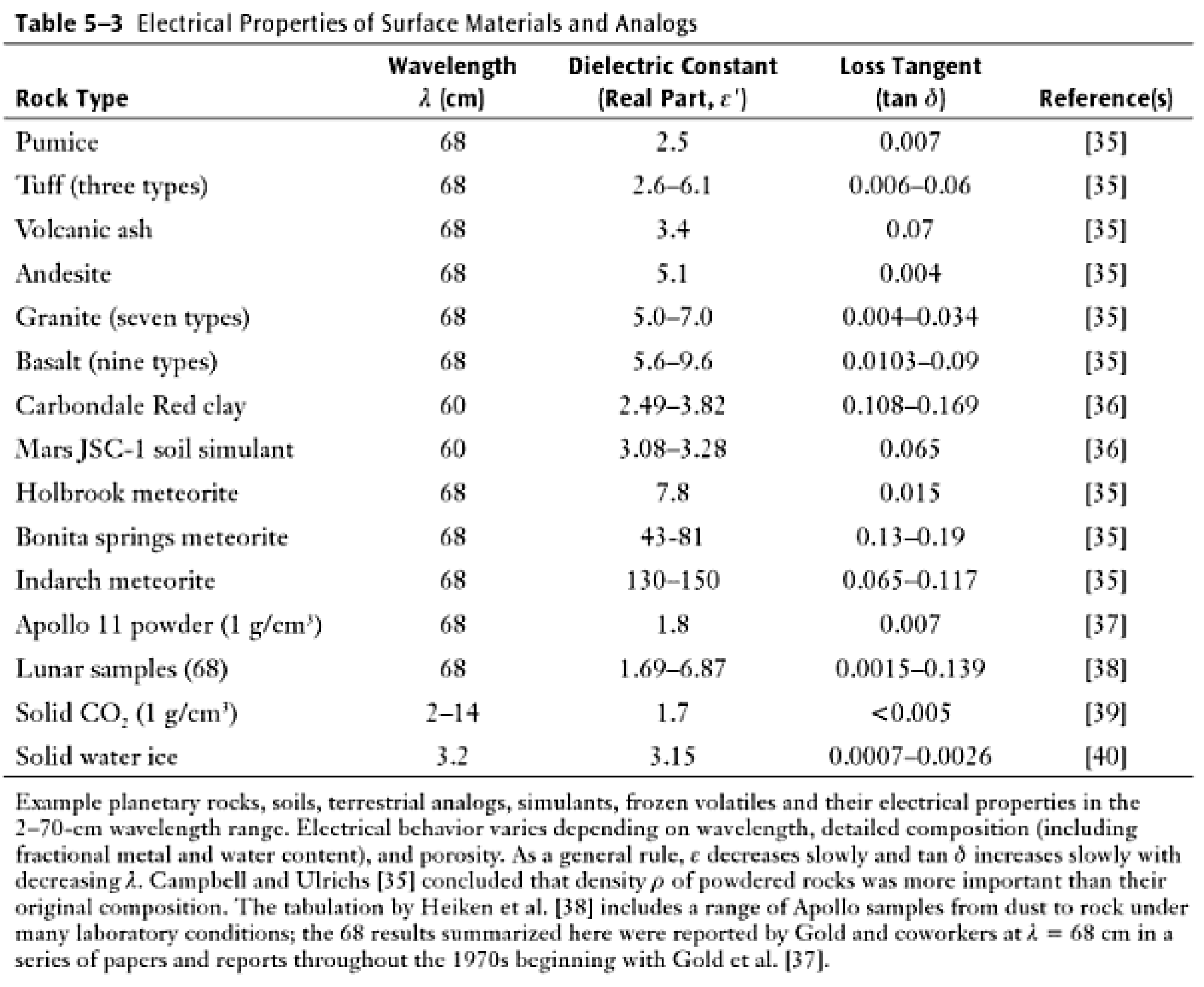


Table 5–3 Electrical Properties of Surface Materials and Analogs

Rock Type	Wavelength λ (cm)	Dielectric Constant (Real Part, ε')	Loss Tangent ($\tan\delta$)	Reference(s)
Pumice	68	2.5	0.007	[35]
Tuff (three types)	68	2.6–6.1	0.006–0.06	[35]
Volcanic ash	68	3.4	0.07	[35]
Andesite	68	5.1	0.004	[35]
Granite (seven types)	68	5.0–7.0	0.004–0.034	[35]
Basalt (nine types)	68	5.6–9.6	0.0103–0.09	[35]
Carbondale Red clay	60	2.49–3.82	0.108–0.169	[36]
Mars JSC-1 soil simulant	60	3.08–3.28	0.065	[36]
Holbrook meteorite	68	7.8	0.015	[35]
Bonita springs meteorite	68	43-81	0.13–0.19	[35]
Indarch meteorite	68	130–150	0.065–0.117	[35]
Apollo 11 powder (1 g/cm^3)	68	1.8	0.007	[37]
Lunar samples (68)	68	1.69–6.87	0.0015–0.139	[38]
Solid CO_2 (1 g/cm^3)	2–14	1.7	<0.005	[39]
Solid water ice	3.2	3.15	0.0007–0.0026	[40]

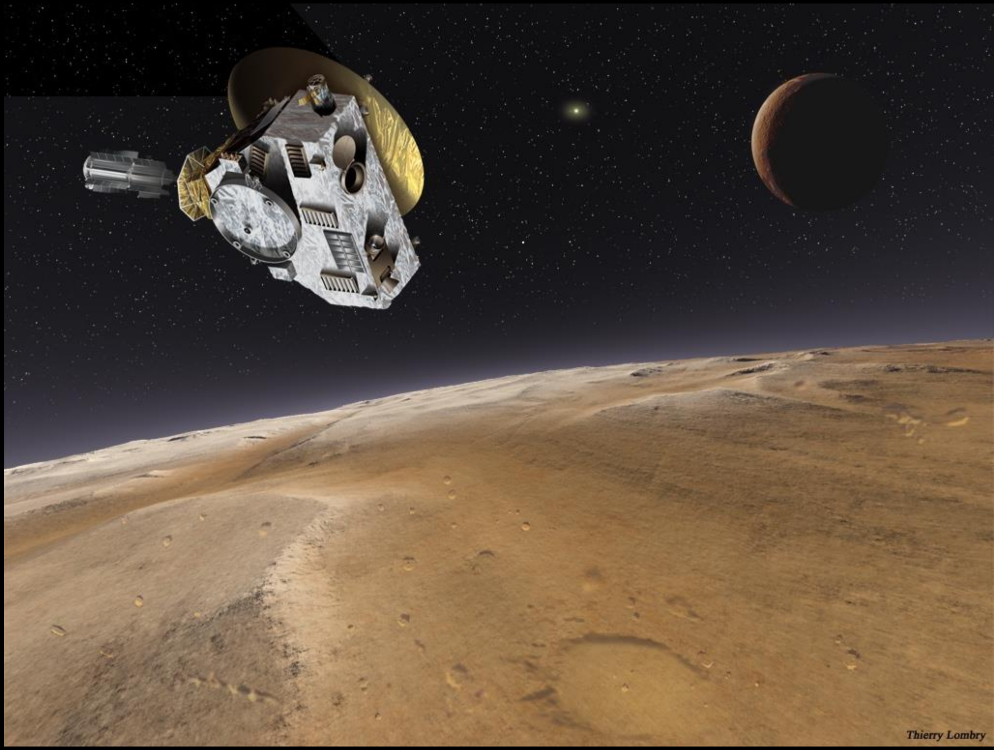
Example planetary rocks, soils, terrestrial analogs, simulants, frozen volatiles and their electrical properties in the 2–70-cm wavelength range. Electrical behavior varies depending on wavelength, detailed composition (including fractional metal and water content), and porosity. As a general rule, ε decreases slowly and $\tan\delta$ increases slowly with decreasing λ. Campbell and Ulrichs [35] concluded that density ρ of powdered rocks was more important than their original composition. The tabulation by Heiken et al. [38] includes a range of Apollo samples from dust to rock under many laboratory conditions; the 68 results summarized here were reported by Gold and coworkers at λ = 68 cm in a series of papers and reports throughout the 1970s beginning with Gold et al. [37].

Pros and Cons

- Pros
  - Estimates of surface materials
  - Cheap! (Piggy-backing)

- Cons
  - Needs a specific range of incidence angles
  - Low resolution

Upcoming: Bistatic Radar at Pluto



Pluto Fly-by in 2015

http://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=2006-001A

Summary

- Earth-based radar can be effectively used to map many planetary surfaces
- Many configurations possible
  - Monostatic/Bistatic, Uplink/Downlink, CW/Pulses…
- Relatively simple and cheap
  - Piggy-backing on existing spacecraft

Thank You!

☺