WATER ICE AT THE LUNAR POLES- A RADAR PERSPECTIVE

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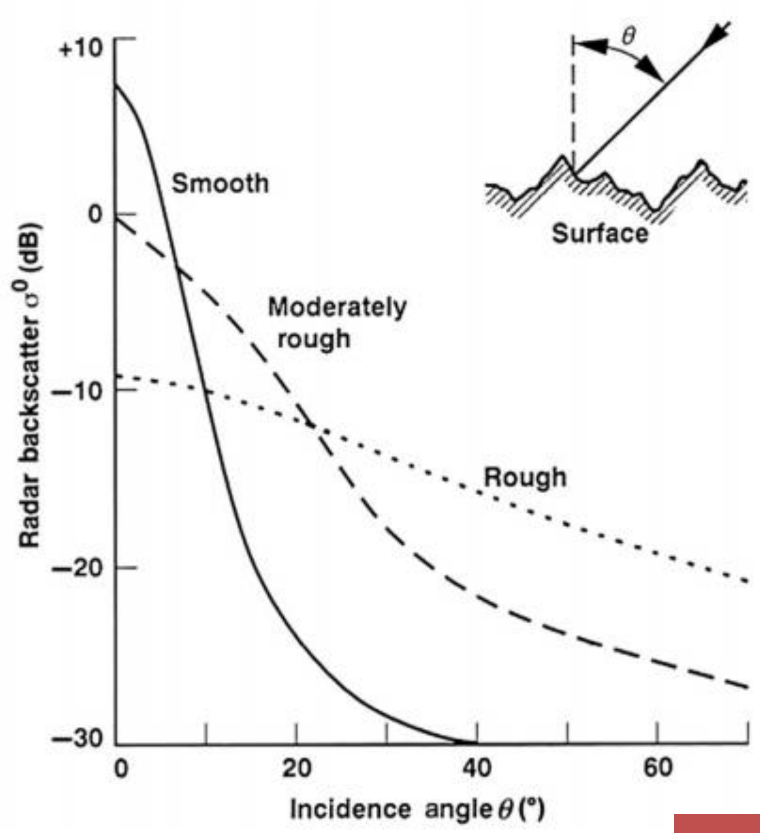
Outline

Radar is a useful remote sensing tool for studying planetary geology because it is sensitive to the composition, structure, electrical properties and roughness of the surface

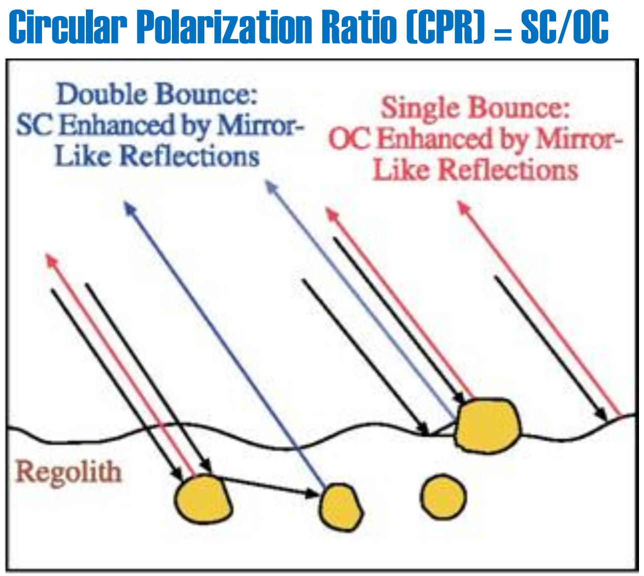
1. *Planetary Radar*
   Introduction to the jargon
2. *Detecting Water Ice*
   Techniques and some prior results from other SS objects
3. *Lunar Poles*
   A Timeline of Radar Observations
4. *A Tale of Two Poles*
   Are the Poles of Mercury and Earth's Moon different?
5. *Current Understanding*
   Where are we now
6. *Way Forward*

Planetary Radar

Radar measurements use all aspects of EM waves: frequency/ wavelength, amplitude, polarization to acquire information

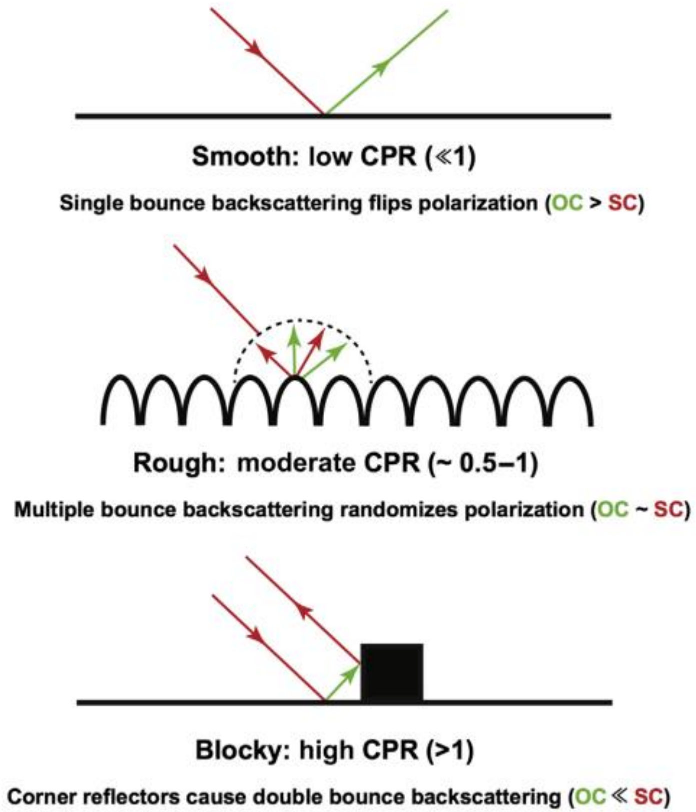


adapted from Farr, T. G. (1993)



A sensitive indicator of near- surface roughness

Campbell et al. JGR (2009)



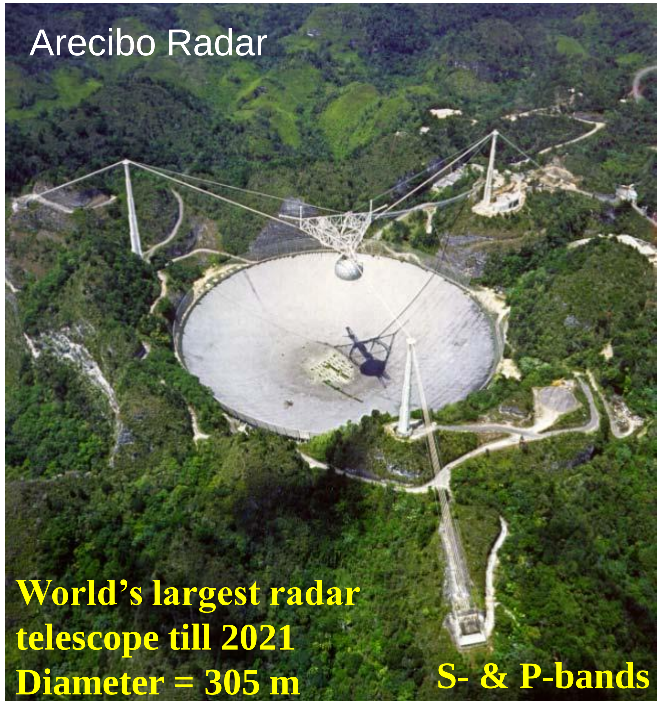
Neish & Carter (2014)

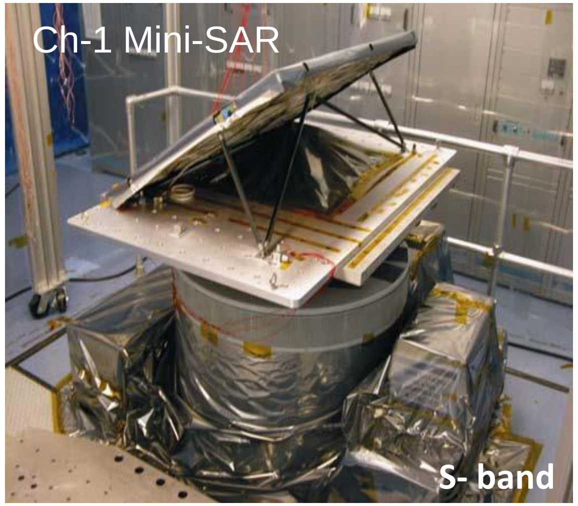
The ability of radar to investigate the lunar subsurface provides a unique perspective with which we can explore geologic processes and their influence on regolith development (including volatiles such as ice)

Radars for Lunar exploration

Ground-based Radars

Orbiting Radars





Tx & Rx: Circular Polarization
(Heritage since 70's: Obtains OC and SC)

Tx: Circular Polarization
Rx: Dual-linear Polarization

Tx: Linear/Circular Polarization
Rx: Dual-linear Polarization

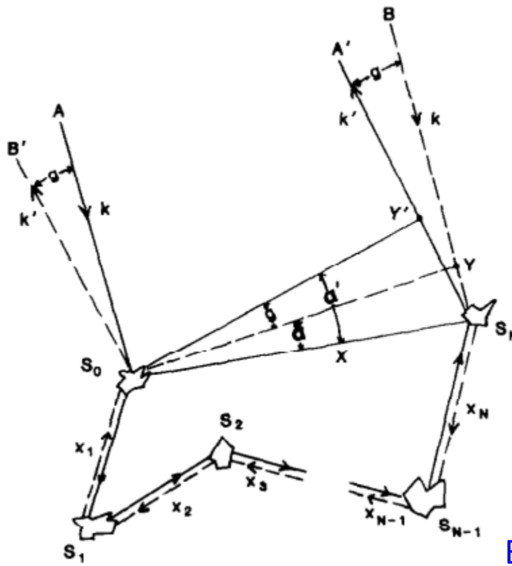
Compact Polarimetry
(One Tx Pol, Coherent Dual Rx)

Full Polarimetry
(Orthogonal Tx Pols, Coherent Dual Rx)

All these Radar instruments can generate the CPR parameter

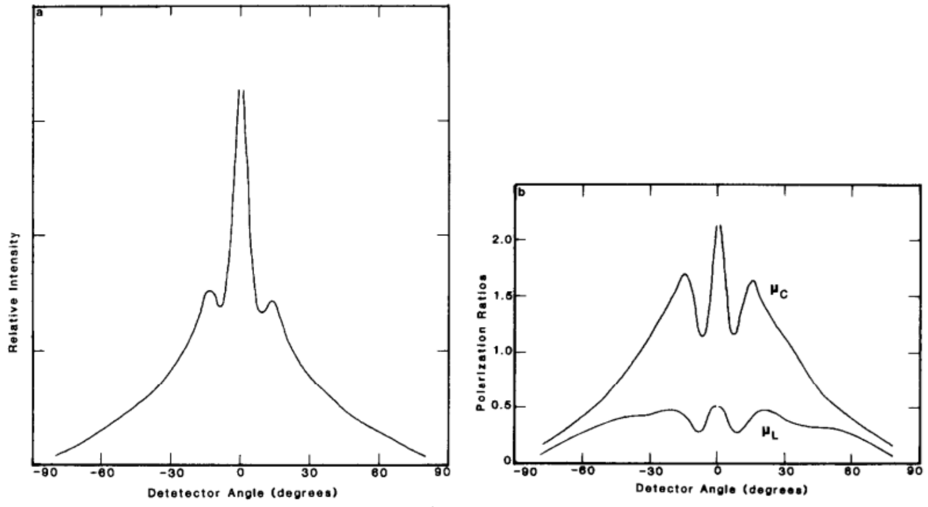
Water Ice: Unique radar properties

Coherent Backscatter Opposition Effect (CBOE) a.k.a Weak Localization a.k.a Time reversal symmetry



Schematic diagram of the CBOE

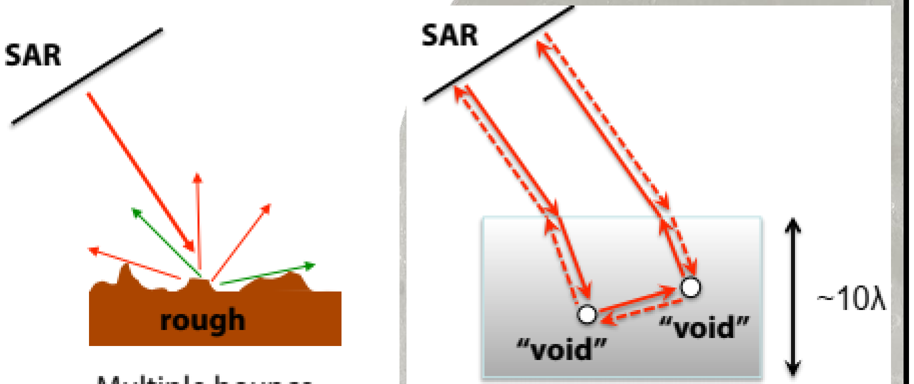
Bruce Hapke, Icarus (1990)



Gold surface experiments

1. Constructive interference between radar signals that follow the same path in opposite directions
2. These signals are **forward scattered**, which preserves the original sense of polarization
3. This leads to large "SC" returns, and high CPRs **(CPR = SC/OC)**
4. CBOE is most effective with **closely spaced, wavelength-sized** scatterers of low refractive index in a weakly absorbing medium

Radar Observations of a target surface



Multiple bounce backscattering on a rough surface randomizes polarization (OC ≈ SC)

MODERATE CPR (~0.5 - 1)

Forward scattering in ice preserves polarization (OC << SC)

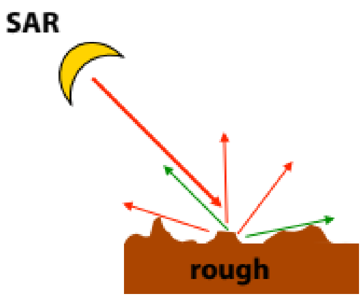
HIGH CPR (> 1)

Neish & Carter (2014)

High, anomalous CPR values

However…

High CPR can also be explained by extremely blocky surfaces



Multiple bounce backscattering on a rough surface randomizes polarization (OC ≅ SC)

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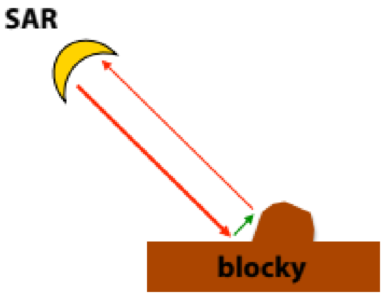
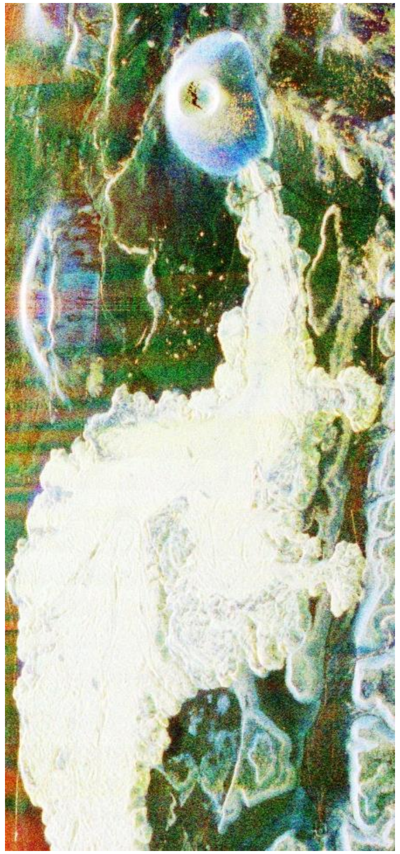


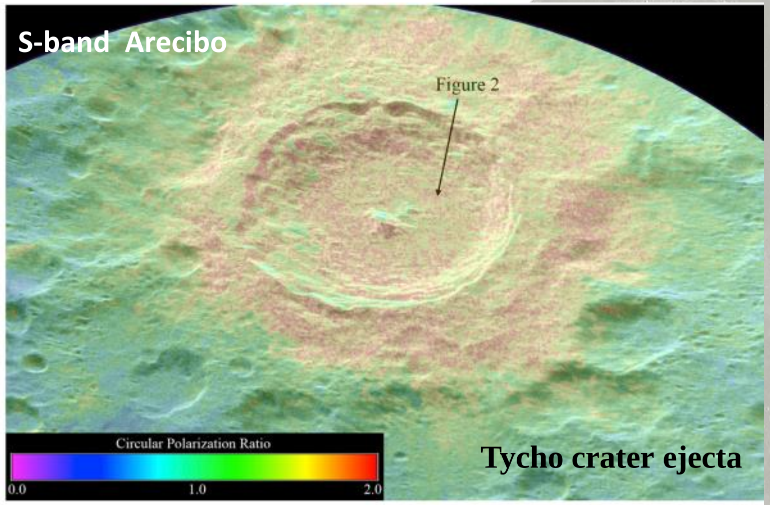
Blocky surfaces may act as corner reflectors, causing double bounce backscatter (OC << SC)

HIGH CPR (> 1)

Neish & Carter, 2014

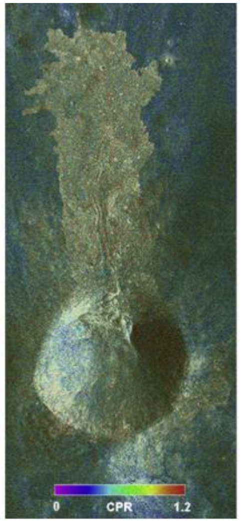


AIRSAR image of SP flow, Arizona

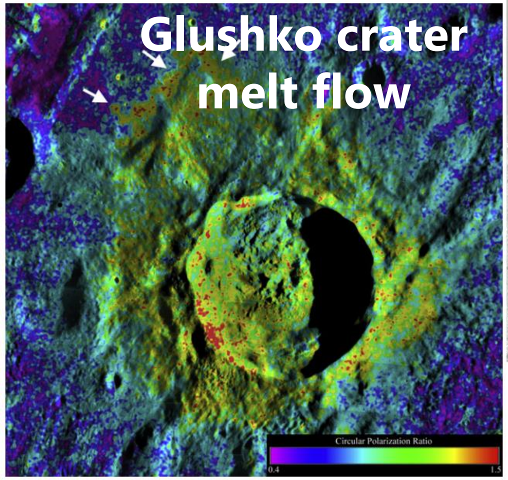


Campbell, JGR (2012)

Donner crater melt flow



Neish et al. Icarus (2014)



Campbell et al. Icarus (2010)

Icy Surfaces in the Solar System – Galilean satellites

Icarus 34, 254–267 (1978)

Galilean Satellites: 1976 Radar Results

DONALD B. CAMPBELL

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AND

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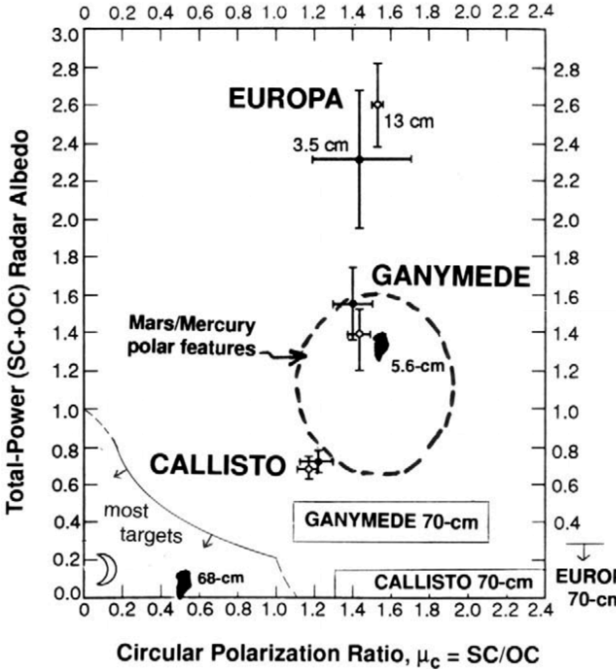
Department of Earth and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

Received August 22, 1977; revised November 18, 1977

Radar observations of the Galilean satellites, made in late 1976 using the 12.6-cm radar system of the Arecibo Observatory, have yielded mean geometric albedos of 0.04 ± 0.01, 0.69 ± 0.17, 0.37 ± 0.09, and 0.15 ± 0.04, for Io, Europa, Ganymede, and Callisto, respectively. The albedo for Io is about 40% smaller than that obtained approximately a year earlier, while the albedos for the outer three satellites average about 70% larger than the values previously reported for late 1975, raising the possibility of temporal variation. Very little dependence on orbital phase is noted; however, some regional scattering inhomogeneities are seen on the outer three satellites. For Europa, Ganymede, and Callisto, the ratios of the echo received in one mode of circular polarization to that received in the other were: 1.61 ± 0.20, 1.48 ± 0.27, and 1.24 ± 0.19, respectively, with the dominant component having the *same* sense of circularity as that transmitted. This behavior has not previously been encountered in radar studies of solar system objects, whereas the corresponding observations with linear polarization are "normal." Radii determined from the 1976 radar data for Europa and Ganymede are: 1530 ± 30 and 2670 ± 50 km, in fair agreement with the results from the 1975 radar observations and the best recent optical determinations. Doppler shifts of the radar echoes, useful for the improvement of the orbits of Jupiter and some of the Galilean satellites, are given for 12 nights in 1976 and 10 nights in 1975.



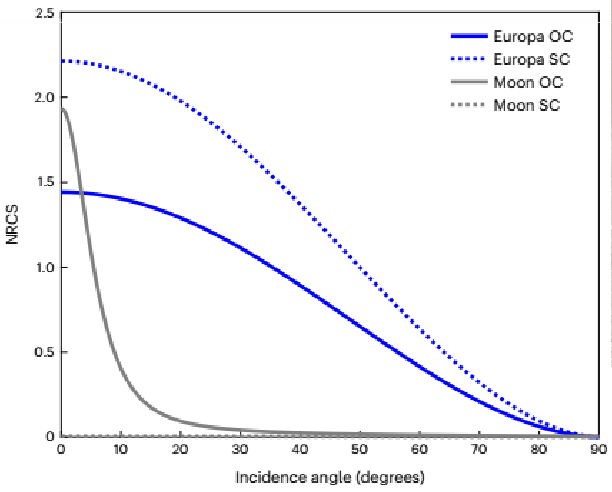
Ostro, 2006

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 97, NO. E11, PAGES 18,227–18,244, NOVEMBER 25, 1992

Europa, Ganymede, and Callisto: New Radar Results From Arecibo and Goldstone

S. J. OSTRO,[1] D. B. CAMPBELL,[2] R. A. SIMPSON,[3] R. S. HUDSON,[4] J. F. CHANDLER,[5] K. D. ROSEMA,[1] I. I. SHAPIRO,[5] E. M. STANDISH,[1] R. WINKLER,[1] D. K. YEOMANS,[1] R. VELEZ,[6] AND R. M. GOLDSTEIN[1]

Observations of the icy Galilean satellites, conducted during 1987-1991 with the Arecibo 13-cm system and the Goldstone 3.5-cm system, yield significant improvements in our knowledge of the satellites' radar properties. Hardly any wavelength dependence is seen for either the total power radar albedo $\hat{\sigma}_T$ or the circular polarization ratio μ_C. For Europa, Ganymede, and Callisto our 13-cm estimates of mean values and rms dispersions are $\hat{\sigma}_T$ = 2.60 ± 0.22, 1.39 ± 0.14, and 0.69 ± 0.06; and μ_C = 1.53 ± 0.03, 1.43 ± 0.06, and 1.17 ± 0.04. Radar albedo features are seen on each satellite. Evidence for μ_C features is lacking, except for indications of a weak hemispheric asymmetry for Callisto. That intersatellite and intrasatellite fractional variations in albedo greatly exceed variations in μ_C is consistent with predictions of coherent backscatter theory and implies that albedo might be a crude indicator of relative silicate abundance. The satellites' albedo distributions overlap. The most prominent radar features are tentatively identified with Galileo Regio and the Valhalla basin. Estimates of echo Doppler frequencies show Callisto to be lagging its ephemeris by 200 ± 50 km.



Hofgartner & Hand, Nat. Astro. (2023)

For the icy Galilean satellites there is no evidence of specular surface reflections at wavelengths from 3.5 up to 70 cm, and their entire echoes are apparently the result of multiple scattering (Campbell et al. 1978; Ostro et al., 1992; Black et al., 2001).

Water ice on the Moon : Background

JOURNAL OF GEOPHYSICAL RESEARCH VOLUME 66, NO. 5 MAY 1961

On the Possible Presence of Ice on the Moon[1]

KENNETH WATSON, BRUCE MURRAY, AND HARRISON BROWN

Division of Geological Sciences
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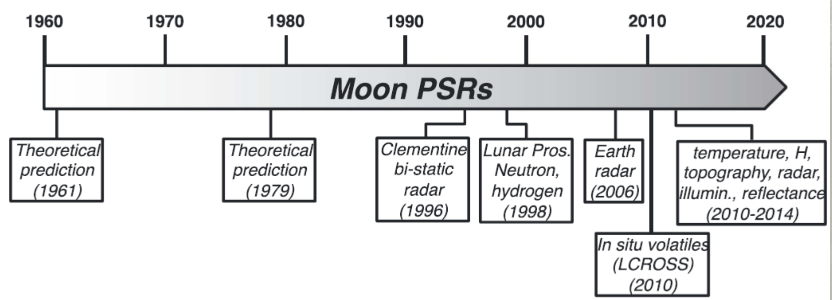
Pasadena, California

It is generally presumed that gases of low molecular weight escape very rapidly from the moon. As a consequence, it has been assumed that volatile substances, such as water, which possess short relaxation times for escape, do not exist there. *Urey* [1952] recognized that there may be depressions in which the sun never shines, and in which some condensed volatile substances could be present, but he concluded that no solid or liquid water could exist on the moon for more than very short periods of time. *Kuiper* [1952], following a suggestion by Herzberg, stated that SO_2 molecules might be concentrated on the night side of the moon. We wish to argue that water is actually far more stable on the lunar than the corresponding pressures of SO_2 and the rare gases. For an isothermal atmosphere and constant gas pressure at the surface (corresponding to the vapor pressure) the mass of the atmosphere per unit area of the lunar surface will be independent of both temperature and molecular weight and will correspond at this vapor pressure to 1.1×10^{-11} g/cm², or to a total lunar atmospheric water mass of 4.2×10^{6} grams. These quantities will of course be very sensitive to the assumed temperature of the coldest area. It should be noted that this estimated pressure of water vapor is not inconsistent with the radio occultation measurements of *Elsmore* [1957].

The three equally important components to the delivery and trapping process for lunar volatiles:

1. Their Source(s)
2. Transport to the Polar Regions
3. Ultimate storage



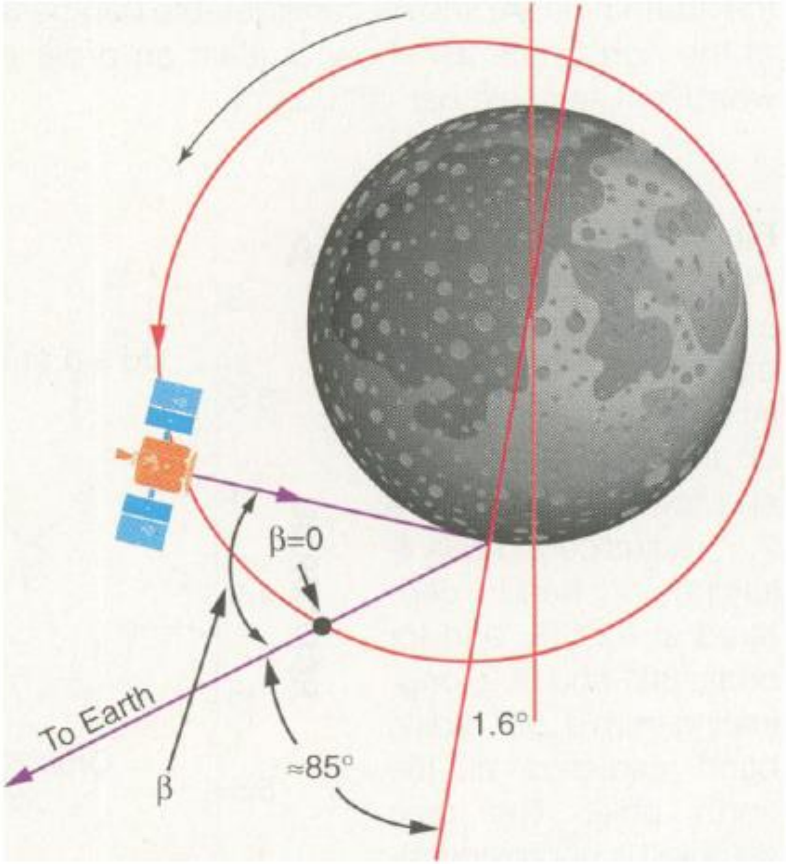
Timeline of PSR exploration for the Moon

Technique	Depth sensed	Detection limit on H_2O	Heritage
UV	~1 µm	< 0.5wt%	LRO LAMP
Shortwave-IR	~10 µm	~10 ppm	M^3
Thermal-IR	~1 – 10 mm	*Unknown*	LRO Diviner
Neutron/gamma ray	~1 m	~100 ppm [H]	LPNS, LEND
Radar	~1 – 10 m	Macroscopic blocks	LRO mini-RF
Passive microwave	Impact vapor plume	~10^{13} H_2O molecules cm^{-2}	Rosetta/MIRO
In-situ gas analysis	Drill/mole	< 1 ppb/g soil	MSL/TLS, Huygens GCMS

Courtesy: KISS report 2014

Comparison of measurement techniques for ice detection and characterization

Lunar Water ice : The Clementine bistatic radar experiment



Orbital geometry of the Clementine bistatic radar experiment

Nozette et al. Science (1996)

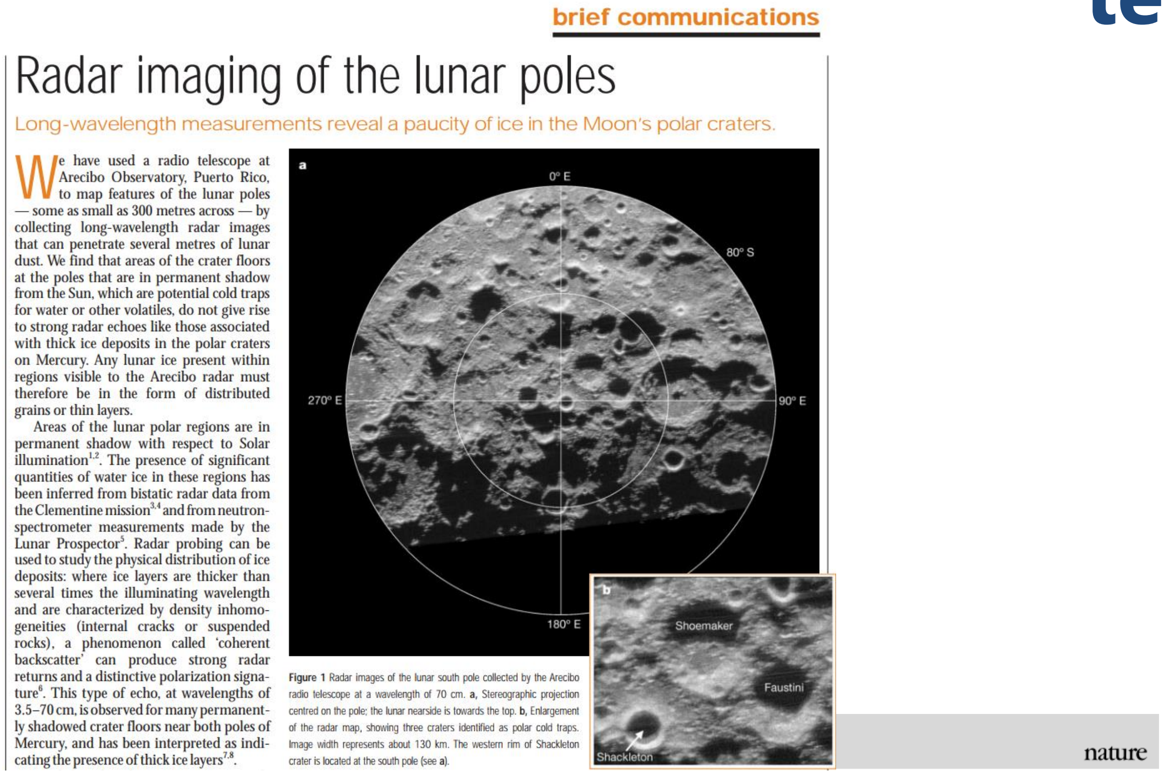
Bistaic radar experiment → Measured the magnitude and polarization of the radar echo versus bistatic angle 'β', for selected lunar areas.

Elevated CPRs → Observed in the south polar region at β close to zero

Results → Suggest the presence of patchy (dirty) ice deposits in the permanently dark areas of Shackleton crater

However, later studies using the same data again (e.g., Simpson & Tyler 1999) indicated that ambiguities still remained, regarding the validity of the ice/no-ice claims

Lunar Water ice : Results from the Arecibo – Green bank telescopes


brief communications

Radar imaging of the lunar poles

Long-wavelength measurements reveal a paucity of ice in the Moon's polar craters.

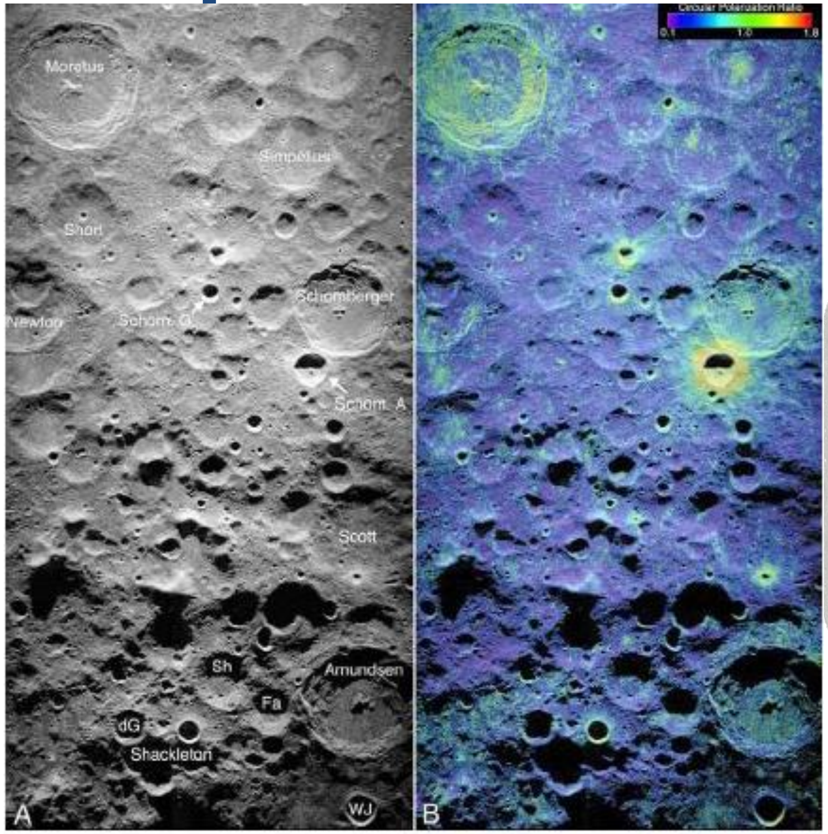
We have used a radio telescope at Arecibo Observatory, Puerto Rico, to map features of the lunar poles — some as small as 300 metres across — by collecting long-wavelength radar images that can penetrate several metres of lunar dust. We find that areas of the crater floors at the poles that are in permanent shadow from the Sun, which are potential cold traps for water or other volatiles, do not give rise to strong radar echoes like those associated with thick ice deposits in the polar craters on Mercury. Any lunar ice present within regions visible to the Arecibo radar must therefore be in the form of distributed grains or thin layers.

Areas of the lunar polar regions are in permanent shadow with respect to Solar illumination[1,2]. The presence of significant quantities of water ice in these regions has been inferred from bistatic radar data from the Clementine mission[3,4] and from neutron-spectrometer measurements made by the Lunar Prospector[5]. Radar probing can be used to study the physical distribution of ice deposits: where ice layers are thicker than several times the illuminating wavelength and are characterized by density inhomogeneities (internal cracks or suspended rocks), a phenomenon called 'coherent backscatter' can produce strong radar returns and a distinctive polarization signature[6]. This type of echo, at wavelengths of 3.5–70 cm, is observed for many permanently shadowed crater floors near both poles of Mercury, and has been interpreted as indicating the presence of thick ice layers[7,8].

Figure 1 Radar images of the lunar south pole collected by the Arecibo radio telescope at a wavelength of 70 cm. a, Stereographic projection centred on the pole; the lunar nearside is towards the top. b, Enlargement of the radar map, showing three craters identified as polar cold traps. Image width represents about 130 km. The western rim of Shackleton crater is located at the south pole (see a).

nature

Campbell, B. A. et al.
Nature (2003)



Radar image data from 24-Oct-2005, for a region covering the south pole and the nearside to latitude ~68° S

Campbell, D.B. et al.
Nature (2006)

LETTERS

No evidence for thick deposits of ice at the lunar south pole

Donald B. Campbell[1], Bruce A. Campbell[2], Lynn M. Carter[2], Jean-Luc Margot[1] & Nicholas J. S. Stacy[3]

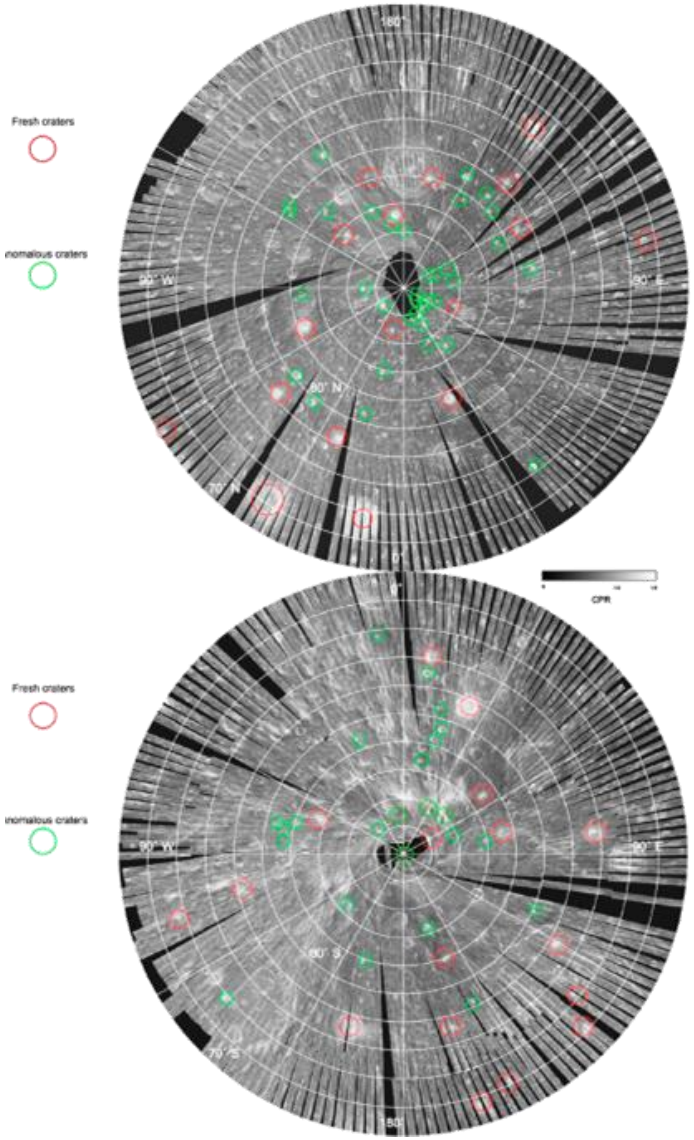
Shackleton crater at the Moon's south pole has been suggested as a possible site of concentrated deposits of water ice, on the basis of modelling of bi-static radar polarization properties and inter- propagates into the ice, is scattered and emerges in the direction of the radar, with its path-reversed twin[12]. Laboratory experiments using lasers on assemblages of particles indicate that volume scatter-

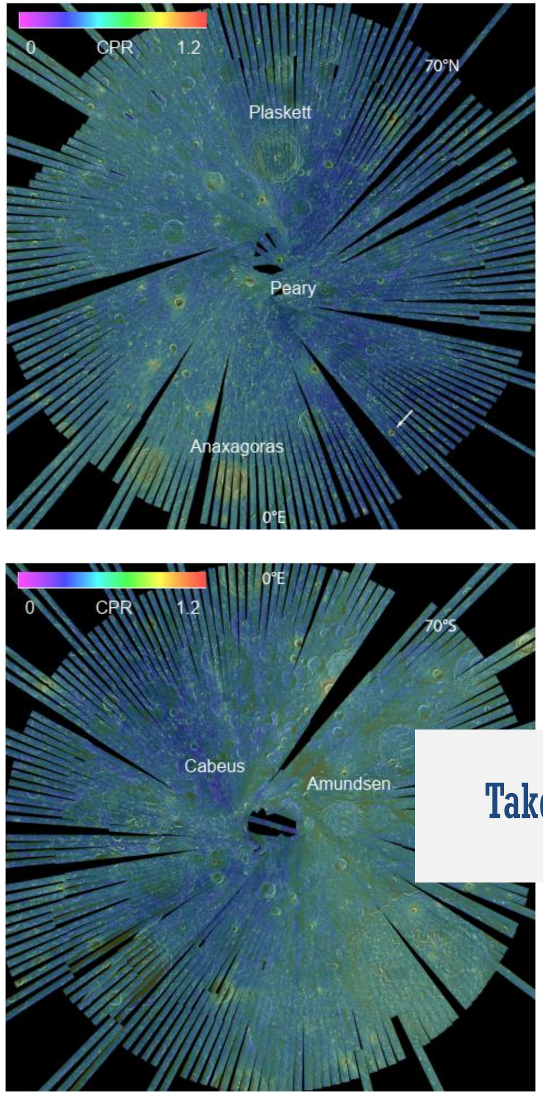
Takeaways

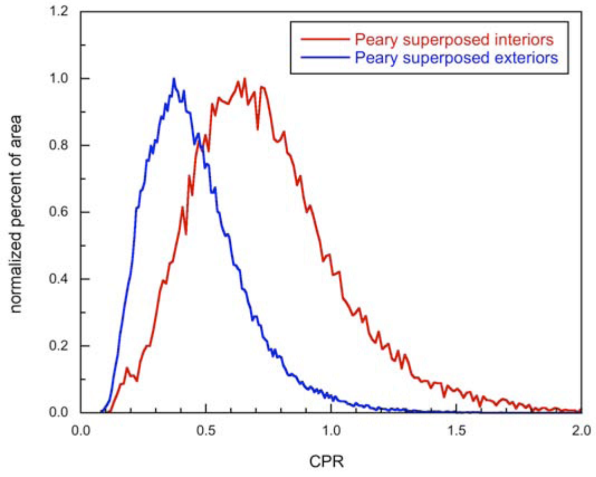
High-resolution S- and P-band radar data show no evidence that high CPR values in Shackleton, or elsewhere in the south polar region, that are correlated with solar illumination conditions.

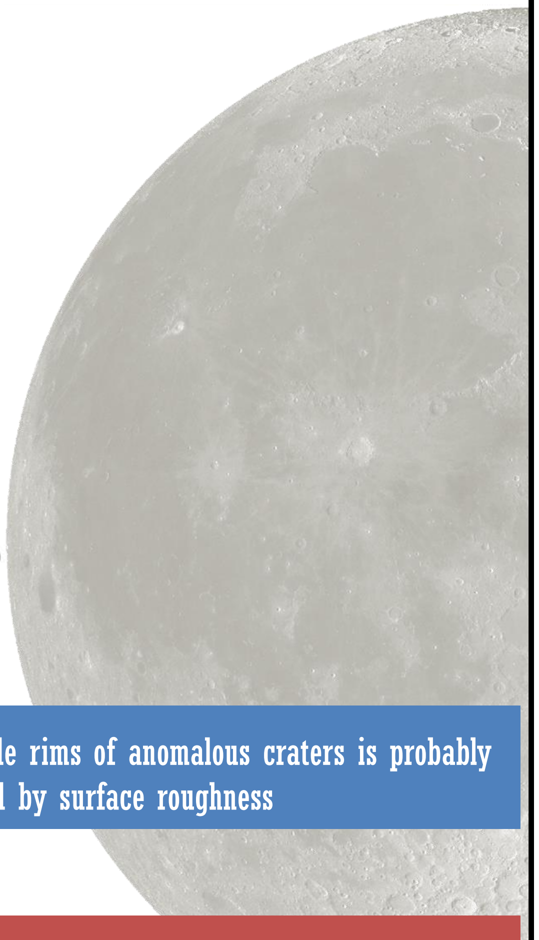
Rather, these high CPR values are associated with the rugged inner walls and proximal ejecta of impact craters

Polar anomalous craters from Mini-RF: Water ice









Takeaways

- The high CPR confined inside rims of anomalous craters is probably not caused by surface roughness
- The elevated CPR, geological occurrence and setting of these features (confined within PS polar regions) and low epithermal neutron flux are all consistent with the presence of water ice in these craters

Spudis et al. GRL (2010); JGR (2015)

Polar anomalous craters from Mini-RF: Surface Roughness

AGU100 ADVANCING EARTH AND SPACE SCIENCE

JGR

Journal of Geophysical Research: Planets

RESEARCH ARTICLE
10.1029/2018JE005668

Unravelling the Mystery of Lunar Anomalous Craters Using Radar and Infrared Observations

Wenzhe Fa[1,2] and Vincent R. Eke[3]

[1]Institute of Remote Sensing and Geographical Information System, Peking University, Beijing, China, [2]Lunar and Planetary Science Laboratory, Macau University of Science and Technology, Macau, China, [3]Institute for Computational Cosmology, Department of Physics, Durham University, Durham, UK

Key Points:
- We constructed orthorectified global Mini-RF mosaics and analyzed anomalous craters in radar and infrared images
- Anomalous craters are not overabundant over the lunar polar regions once sampling variations are accounted for
- Anomalous craters actually represent an intermediate stage of normal crater evolution

Supporting Information:
- Supporting Information S1
- Data Set S1

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Citation:

Abstract In Miniature Radio Frequency (Mini-RF) radar images, anomalous craters are those having a high circular polarization ratio (CPR) in their interior but not exterior to their rims. Previous studies found that most CPR-anomalous craters contain permanently shadowed regions and that their population is overabundant in the polar regions. However, there is considerable controversy in the interpretation of these signals: Both water ice deposits and rocks/surface roughness have been proposed as the source of the elevated CPR values. To resolve this controversy, we have systematically analyzed >4,000 impact craters with diameters between 2.5 and 24 km in the Mini-RF radar image and Diviner rock abundance (RA) map. We first

JGR Planets

RESEARCH ARTICLE
10.1029/2019JE006006

Modeling Radar Albedos of Laboratory-Characterized Particles: Application to the Lunar Surface

Anne K. Virkki[1] and Sriram S. Bhiravarasu[2]

[1]Arecibo Observatory, University of Central Florida, Arecibo, Puerto Rico, [2]Lunar and Planetary Institute, Universities Space Research Association, Houston, TX, USA

Key Points:
- A systematic difference in the radar signatures of internal and external regions of lunar craters is shown
- The role of size, shape, and composition of wavelength-scale particles on the radar signatures is presented
- The circular-polarization ratio is shown to be a non-linear measure of wavelength-scale particle abundance

Supporting Information:
- Supporting Information S1
- Figure S1
- Figure S2
- Figure S3
- Figure S4
- Figure S5
- Figure S6
- Figure S7

Abstract We analyze lunar images obtained by the Mini Radio Frequency instrument onboard the Lunar Reconnaissance Orbiter to interpret the anomalous radar scattering observed in some lunar craters. We compare the radar signatures of the crater floors to those of the regions external to the crater rim and show that there is a systematic difference between the radar albedo trends of the two regions. Using numerical simulations to compute radar scattering properties of rock and ice particles, we demonstrate that the difference is caused partly by the near-surface bulk volume density or the underlying fine-grained regolith and partly by the shape and size distributions of centimeter-to-decimeter-scale rubble. We show that while the size distribution of wavelength-scale particles plays the major role in the observed radar albedos, if the size distribution is fixed, the particle shapes can play a greater role than the composition; therefore, the icy material is indistinguishable from silicate-rich material unless the abundance of ice in the particles plays a major role in the shape of the particles.

Circular polarization ratio characteristics of impact craters from Mini-RF observations and implications for ice detection at the polar regions of the Moon

Wenzhe Fa[1] and Yuzhen Cai[1]

Received 9 March 2013; revised 29 June 2013; accepted 5 July 2013.

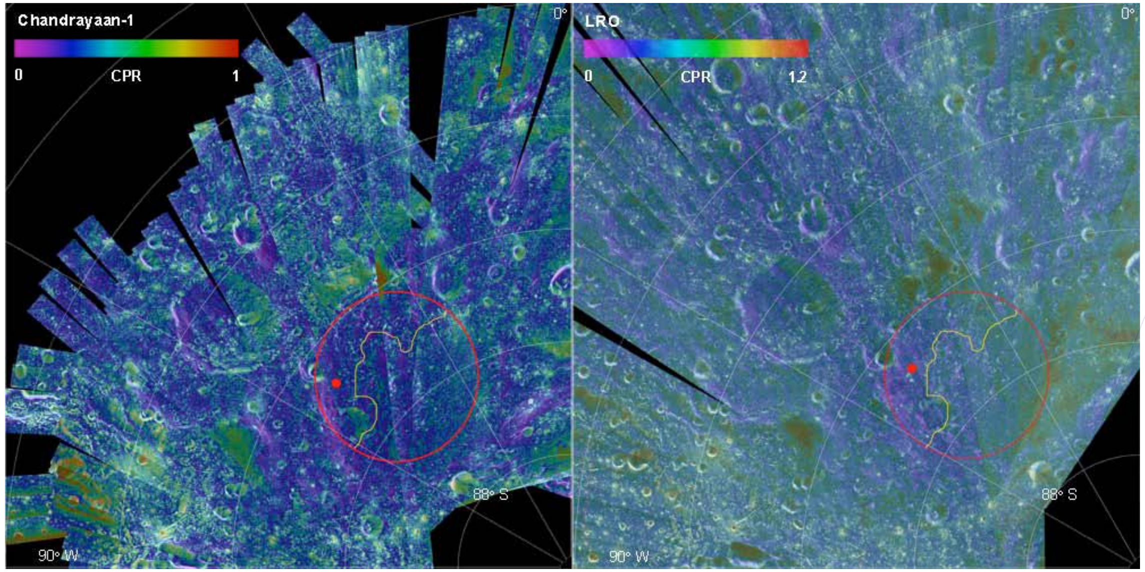
[1] In an attempt to reduce the ambiguity on radar detection of water ice at the permanently shadowed regions near the lunar poles, radar echo strength and circular polarization ratio (CPR) of impact craters are analyzed using the Miniature Radio Frequency (Mini-RF) radar data from the Lunar Reconnaissance Orbiter mission. Eight typical craters, among over 70 craters, are selected and classified into four categories based on their locations and CPR characteristics: polar anomalous, polar fresh, nonpolar anomalous, and nonpolar fresh. The influences on CPR caused by surface slope, rocks, and dielectric constant are analyzed quantitatively using high-resolution topography data and optical images. A two-component mixed model for CPR that consists of a normal surface and a rocky surface is developed to study the effect of rocks that are perched on lunar surface and buried in regolith. Our analyses show that inner wall of a typical bowl-shaped crater can give rise to a change of about 30° in local incidence angle of radar wave, which can further result in a CPR difference of about 0.2. There is a strong correlation between Mini-RF CPR and rock abundance that is obtained from high-resolution optical images, and predictions from the two-component mixed model match well with the observed CPRs and the estimated rock abundances. Statistical results show that there is almost no apparent difference in CPR characteristics between the polar and nonpolar anomalous craters, or between the polar and nonpolar fresh craters. The enhanced CPR in the interior of anomalous craters is most probably caused by rocks that are perched on lunar surface or buried in regolith, instead of ice deposits as suggested in previous studies.

No apparent differences in the CPRs between the polar, potentially icy, and non-polar, not icy craters

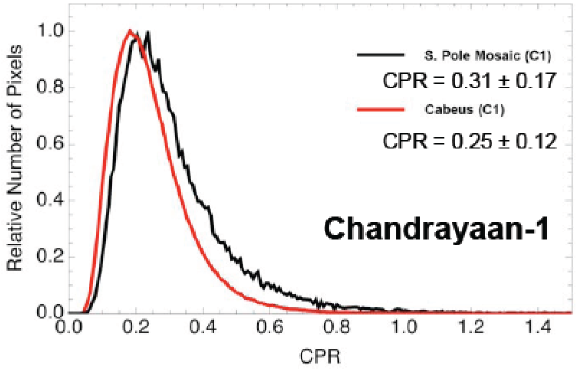
Ice particles are indistinguishable from silicate-rich rock particles unless we can be certain that ice plays a major role in the shape of the particles

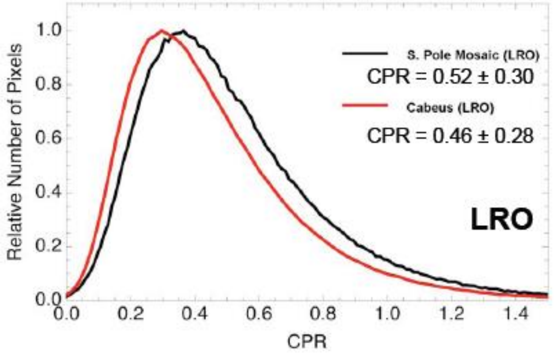
Cabeus crater and the LCROSS impact

S-band Mini-RF radars



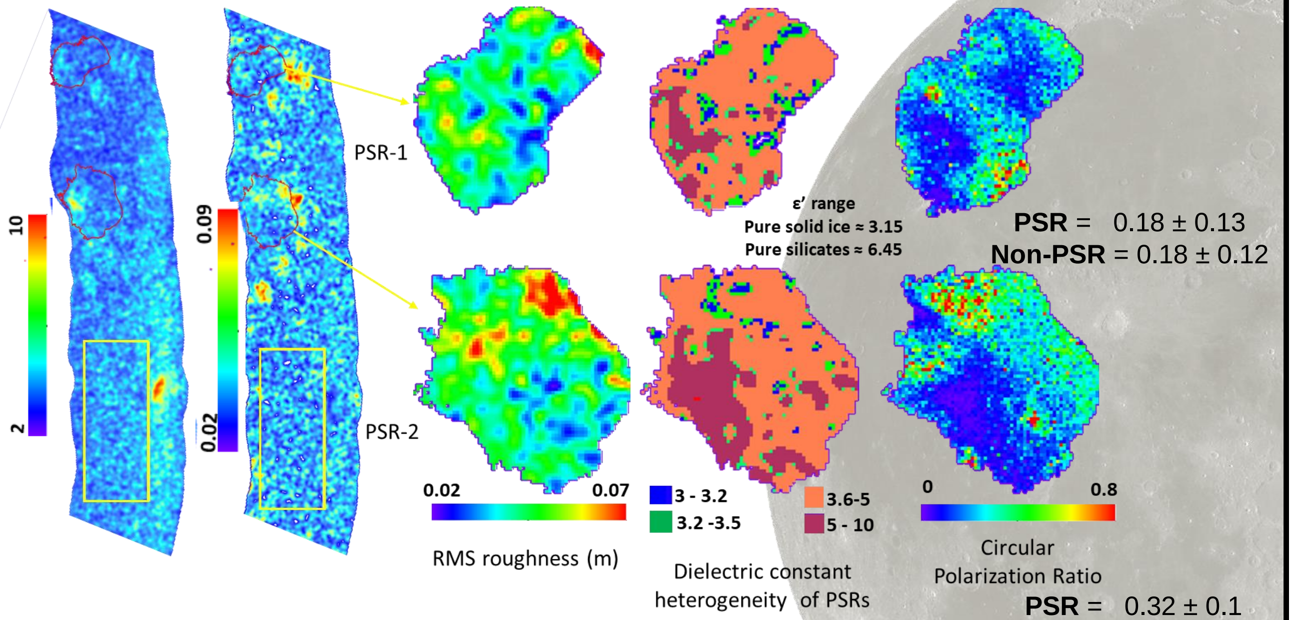
● = approximate location of LCROSS impactor





Neish et al. JGR(2011)

L-band DFSAR results



Bhiravarasu et al. LPSC (2021)

Not consistent with the presence of thick deposits of nearly pure water ice within a few meters of the lunar surface, but does not rule out the presence of small (<~10 cm), discrete pieces of ice mixed in with the regolith

CBOE : Need for non-zero phase angle measurements

LETTERS TO NATURE

Coherent backscatter model for the unusual radar reflectivity of icy satellites

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RADAR is a powerful technique for probing the surfaces and subsurfaces of Solar System bodies. Inner Solar System bodies reflect radar in an almost specular fashion, with low reflectivity and little polarization. The icy satellites of Jupiter, by contrast, show high reflectivities, diffuse scattering laws and unusual polarization properties[1]: compared with what would be expected for specular reflection, there is 1.5 times as much power reflected in the unexpected sense of circularly polarized radar as in the expected sense, and half as much power in the unexpected as in the expected sense of linear polarization. According to the coherent backscatter model[2], most of the received power from icy satellites is multiply reflected by particles about a wavelength in size located randomly under the surface of the regolith. We have constructed a laboratory analogue of this model by reflecting laser light off polystyrene beads suspended in water, and find that this model reproduces the unusual polarization ratios observed in the radar data. This implies that the regoliths of icy satellites are weakly absorbing matrices of small refractive index containing imbedded scatterers separated by distances of the order of a wavelength. No structures of special shape or other geometrical or optical properties are required.

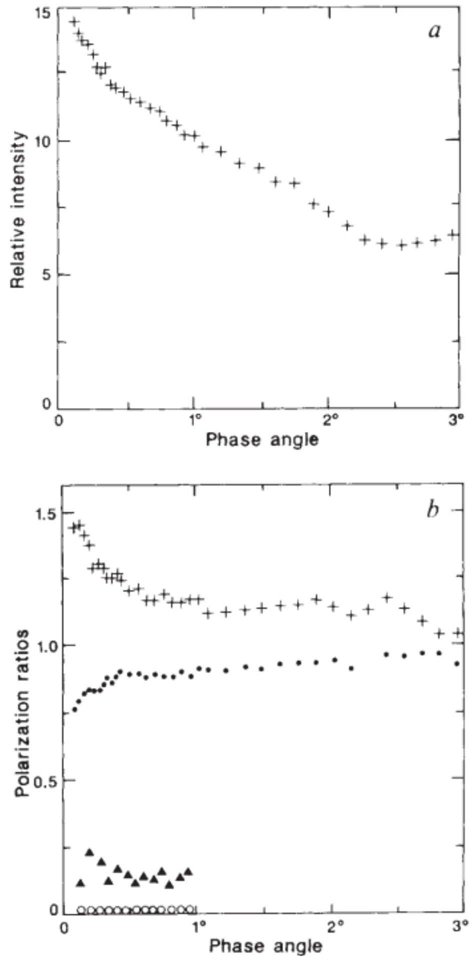
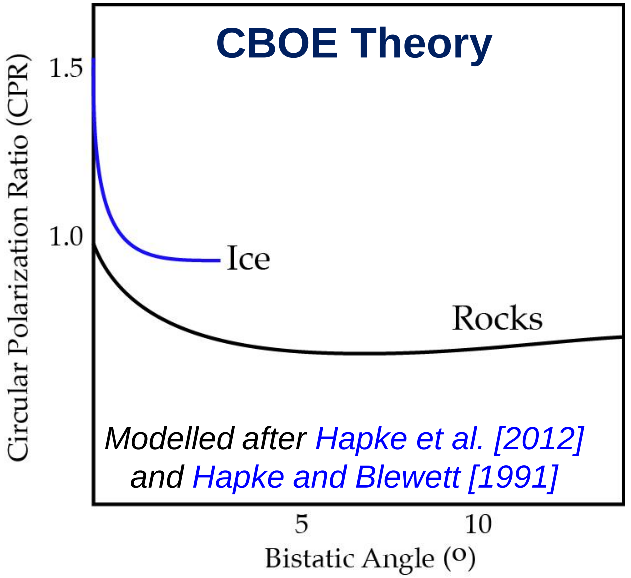
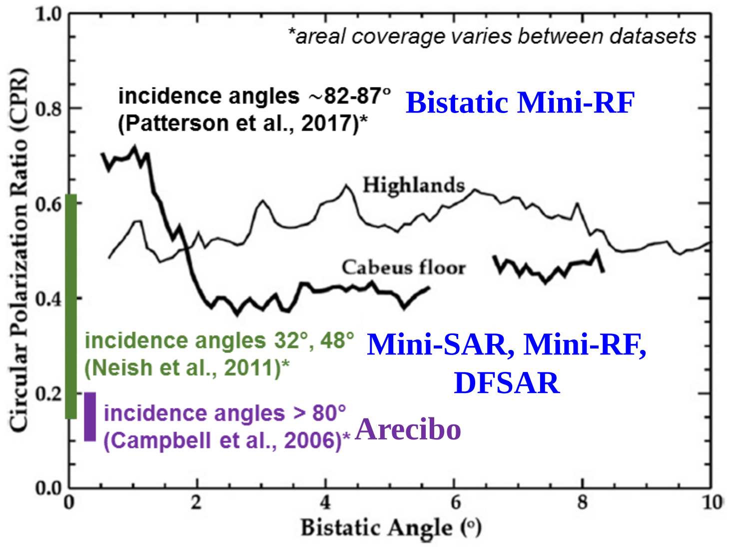


FIG. 1 Relative intensity (*a*) and circular (+) and linear (●) polarization ratios (*b*) plotted against phase angle of light scattered from a suspension of polystyrene spheres in water. Also shown in the lower part of *b* are the linear (○) and circular (▲) polarization ratios of light specularly reflected from the surface of a silicate glass.

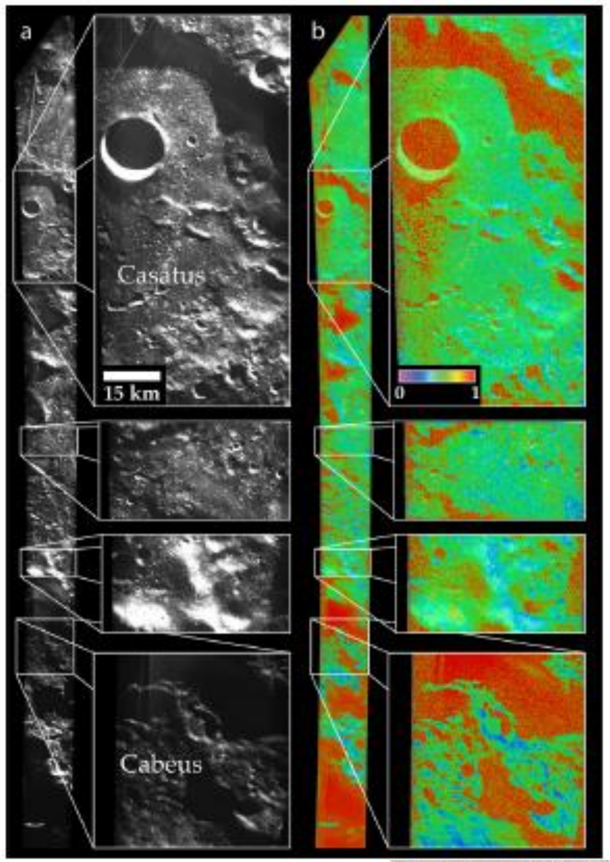
Hapke & Blewett, Nature (1991)

Mini-RF bistatic radar observations of Cabeus





The opposition surge observed for the floor of Cabeus differs from that of crater ejecta and appears unique with respect to all other lunar terrains observed.

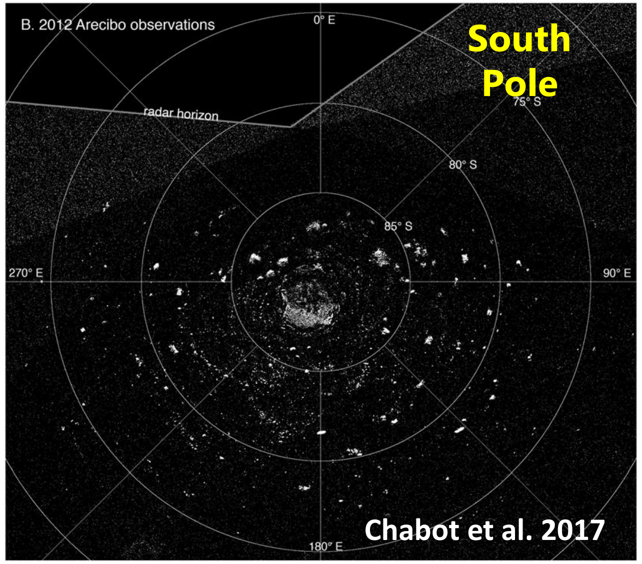


Mini-RF S-band bistatic images of Cabeus region at the lunar south pole

However, understanding the differences between Mini-RF bistatic observations of Cabeus and observations gathered by monostatic DFSAR & Mini-RF, and ground-based radar observations of the crater, remains an open issue

(Patterson et al. Icarus, 2016)

A tale of two poles: Mercury vs the Moon



Arecibo *S*-band Radar Characterization of Local-scale Heterogeneities within Mercury's North Polar Deposits

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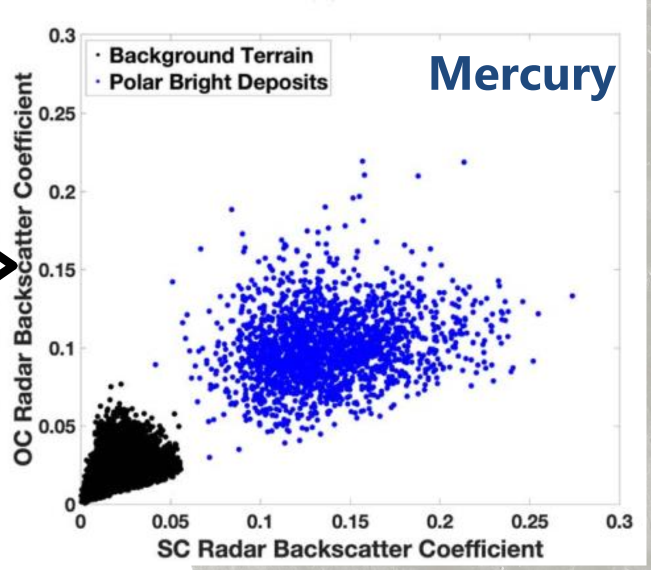
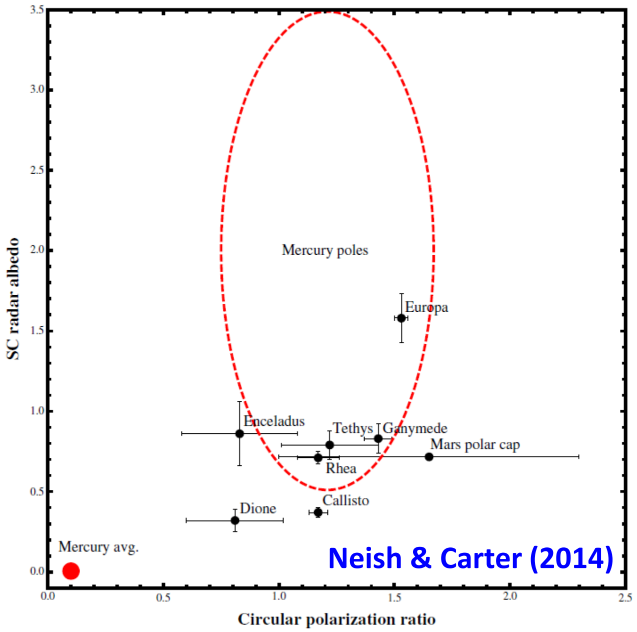
Abstract

Ground-based planetary radar observations first revealed deposits of potentially nearly pure water ice in some permanently shadowed regions (PSRs) on Mercury's poles. Later, the MESSENGER spacecraft confirmed the icy nature of the deposits, as well as their location within PSRs. Considering the geologic context provided by MESSENGER, we further characterized the north polar deposits by pairing spacecraft data with new Arecibo *S*-band radar observations. Here we show that some ice deposits within PSRs have a gradational pattern in their radar properties that is likely associated with differences in ice purity. Radar-bright features with a circular polarization ratio $\mu_c > 1$ can be characterized by water ice with $\gtrsim 3\%$ impurities by volume while those with $\mu_c < 1$ by $\gtrsim 20\%$ impurities. Furthermore, areas in PSRs with $\mu_c < 1$ typically surround locations of stronger radar backscatter with $\mu_c > 1$. Therefore, deposits of nearly pure water ice are likely surrounded by lower-purity material, such as water-ice-rich regolith, which could be the result of impact gardening or the crater's thermal environment. However, such deposits are not always colocated within large polar craters where ice should be the most stable, even at the surface. In fact, we found that there is no significant difference between the radar backscattering properties of deposits thought to have surficial ice and those with buried ice. Our results also help improve the identification of icy reservoirs elsewhere, such as the Moon. Indeed, we found that μ_c is not an adequate diagnostic, but rather the radar backscatter in each circular polarization independently provides information to identify water-ice deposits.

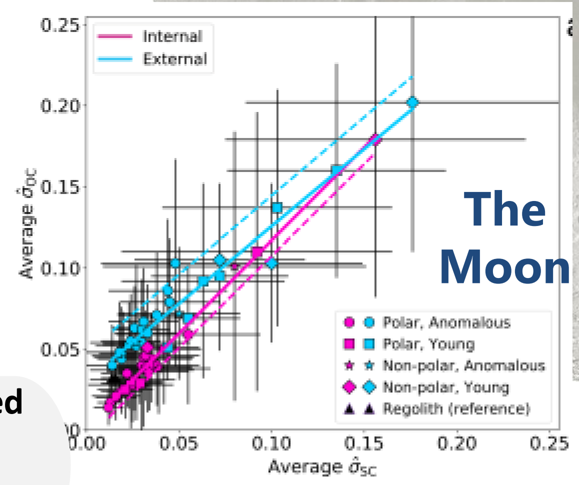




1. The PSRs of the Moon and Mercury have very cold temperatures (<120 K) and as a consequence act as traps for volatile materials

2. Stunning contrast in the radar properties of the polar deposits on Mercury and the Moon

3. One of the most important unanswered questions is why the PSR volatile concentrations at the Moon and Mercury are so different



Virkki & Bhiravarasu, JGR (2019)

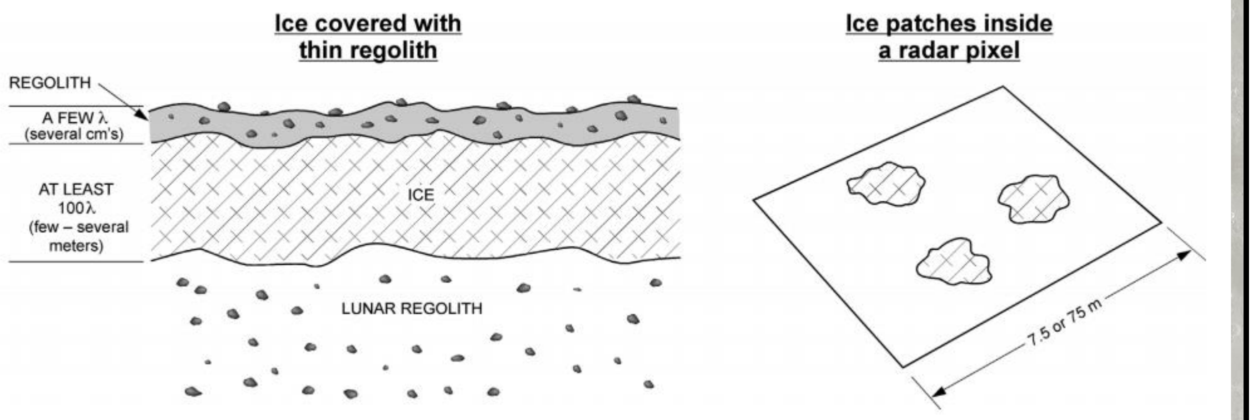
Lunar Water ice : Status quo

Current State

Dirty / Subsurface ice — Ice may be "dirty" and/or present at depths beyond radar penetration

Mercury vs Moon — Regions of less pure ice within Mercury's PSRs are characterized by CPR < 1, which may also be occurring on the Moon

Bistatic Observations — Only Cabeus floor has shown a response so far; and not comparable with monostatic results



Example scenarios for modelling of lunar ice

Courtesy: Thompson et al. JGR (2011)

Lunar Water ice : Way Forward

Current State

Dirty / Subsurface ice — Ice may be "dirty" and/or present at depths beyond radar penetration

Mercury vs Moon — Regions of less pure ice within Mercury's PSRs are characterized by CPR < 1, which may also be occurring on the Moon

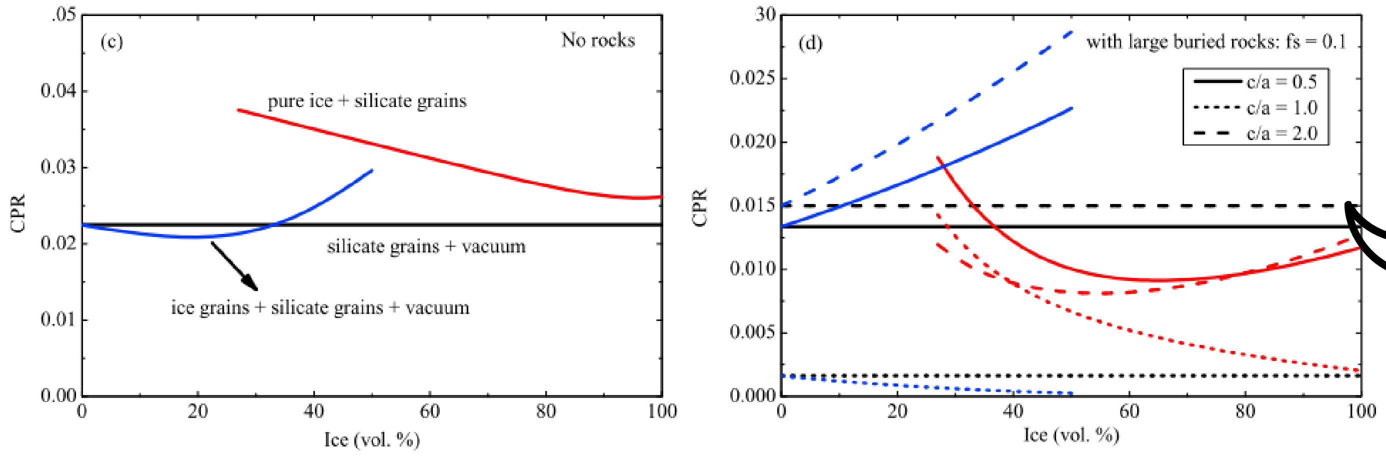
Bistatic Observations — Only Cabeus floor has shown a response so far; and not comparable with monostatic results

Ongoing / Future work

Realistic scattering models to understand the radar return from terrains where: (i) the regolith contains ice inclusions (ii) ice is buried beneath regolith, and (iii) ice includes a significant volume fraction of rocks

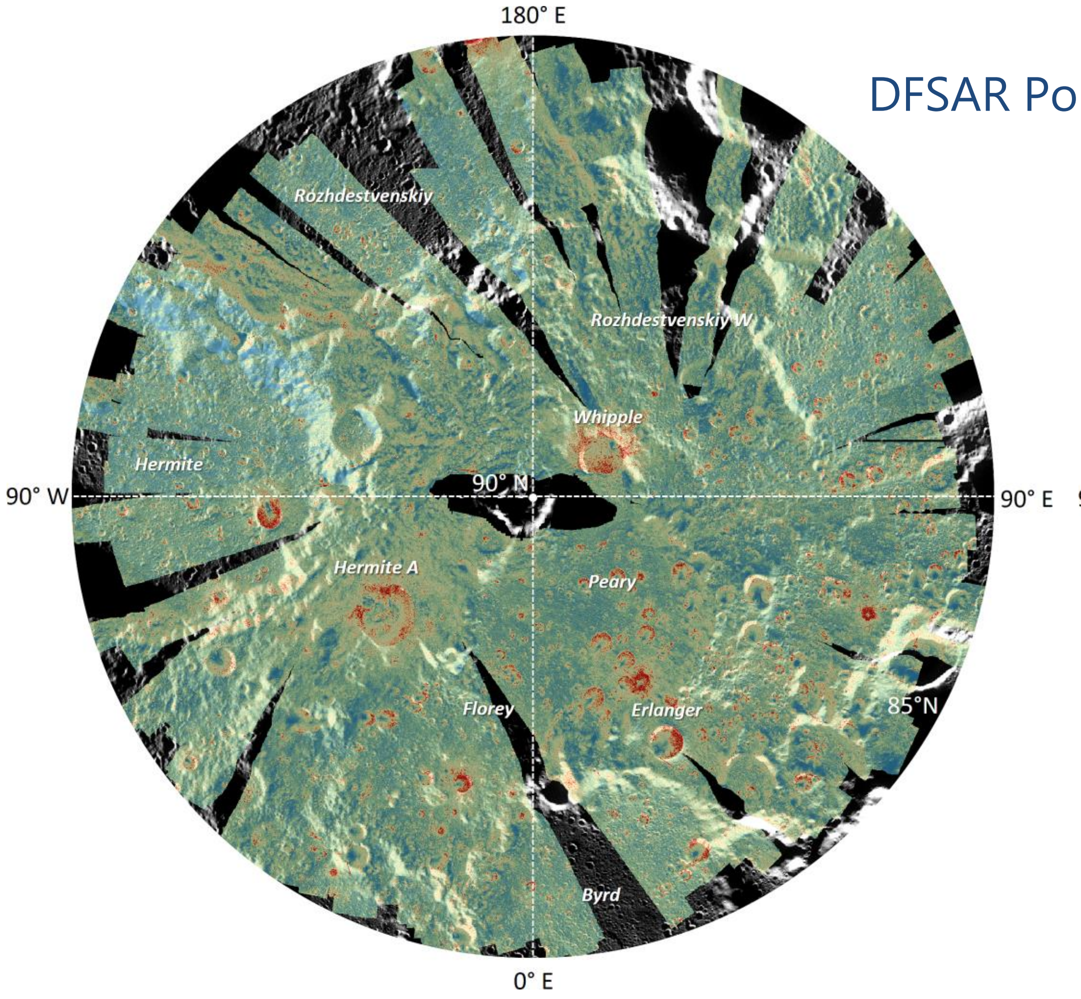
Analysis of CPR<1 regions at lunar poles with new radar data (e.g. fully polarimetric DFSAR, monostatic vs bistatic) in conjunction with other wavelength observations (e.g. TIR, Neutron data)

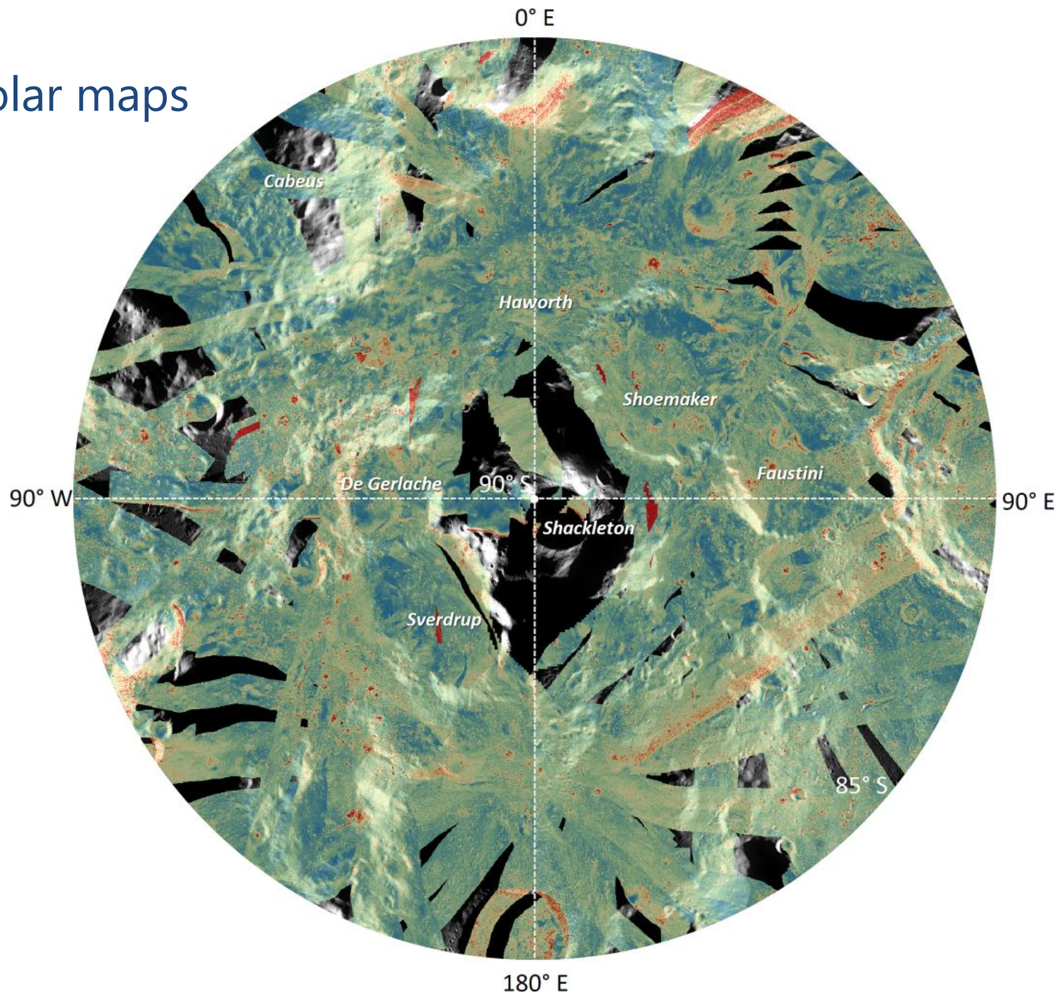
Need more polar bistatic observations !
e.g.: DFSAR Tx with Rx at ground (DSS, GBO) at multiple incidence and phase angles



Fa et al. JGR (2011) model to quantify how the dielectric constant and CPR vary as a function of the abundance of ice in the regolith: in this ice model, the surface layer is a mixture of silicate grains, ice grains, and 50% vacuum

DFSAR Polar maps





THANK YOU !