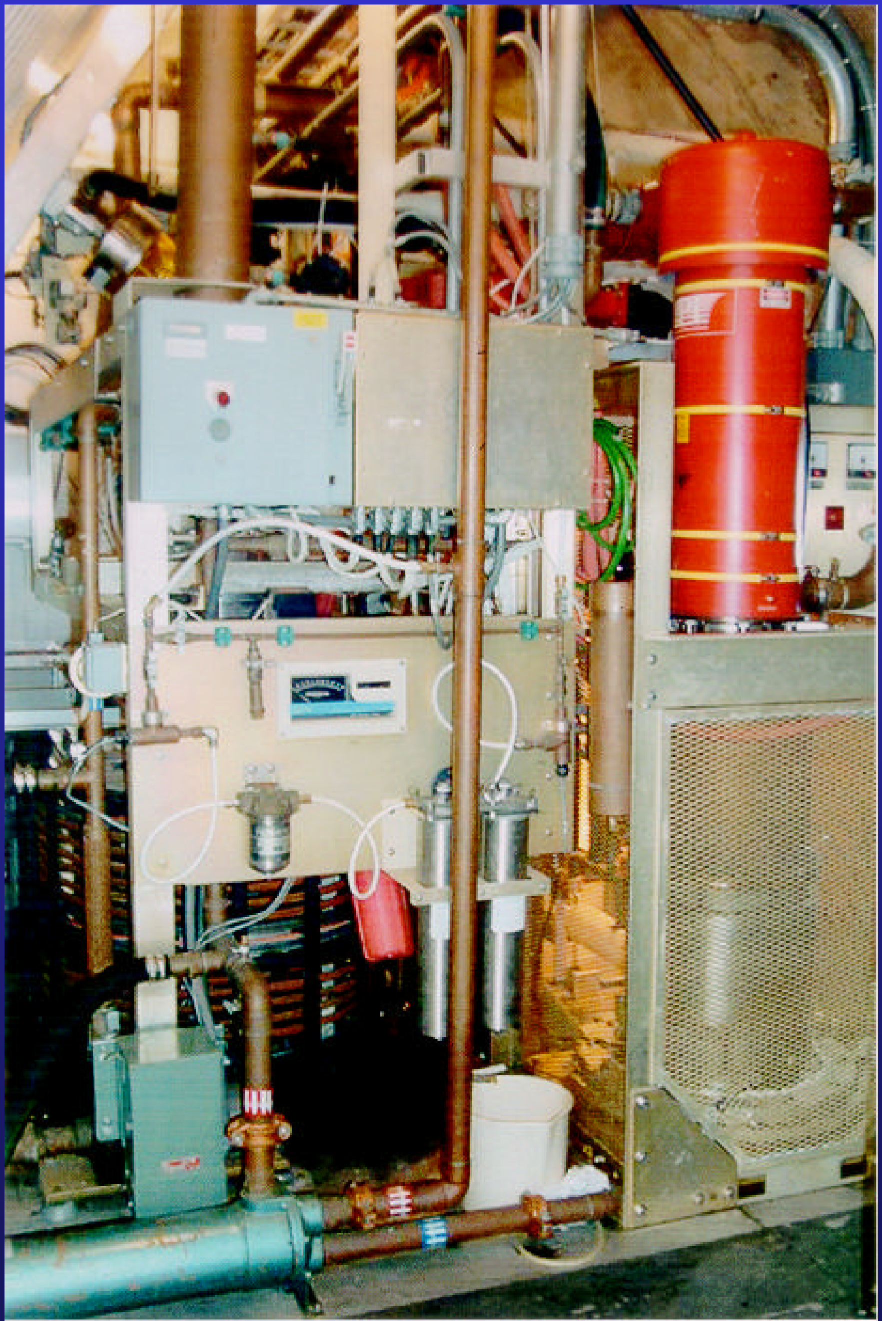
PLANETARY RADAR ASTRONOMY

or

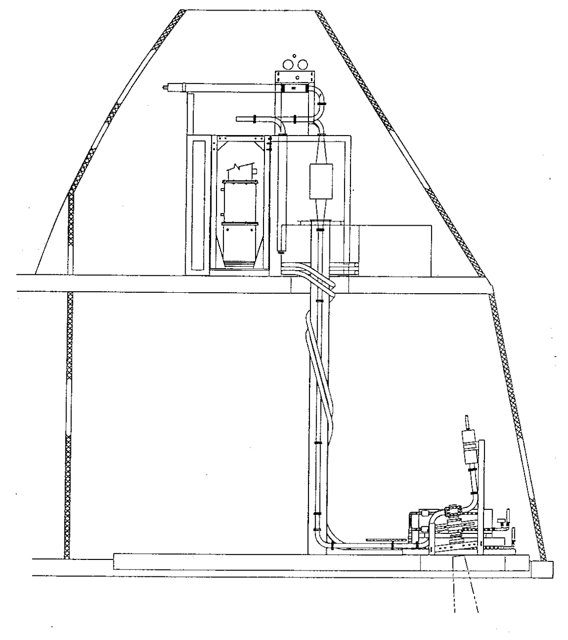
STUDYING SOLAR SYSTEM BODIES WITH RADAR

DON CAMPBELL

NAIC




Transmitter S-Band



PLANETARY RADAR ASTRONOMY

GOOD ASPECTS

Transmitted signal

Can control: **Power**
Polarization
Frequency
Time reference

Received echo

Examine target induced changes in properties of the transmitted signal – provides information about the target - e.g. time delay of a pulse tells you the distance to the target

PLANETARY RADAR ASTRONOMY

NOT SO GOOD ASPECTS

- **Sensitivity is a major problem:**

  Require

  Very high gain transmitting antennas*
  Very large receiving antennas
  Very high powered transmitters
  Very low noise receivers

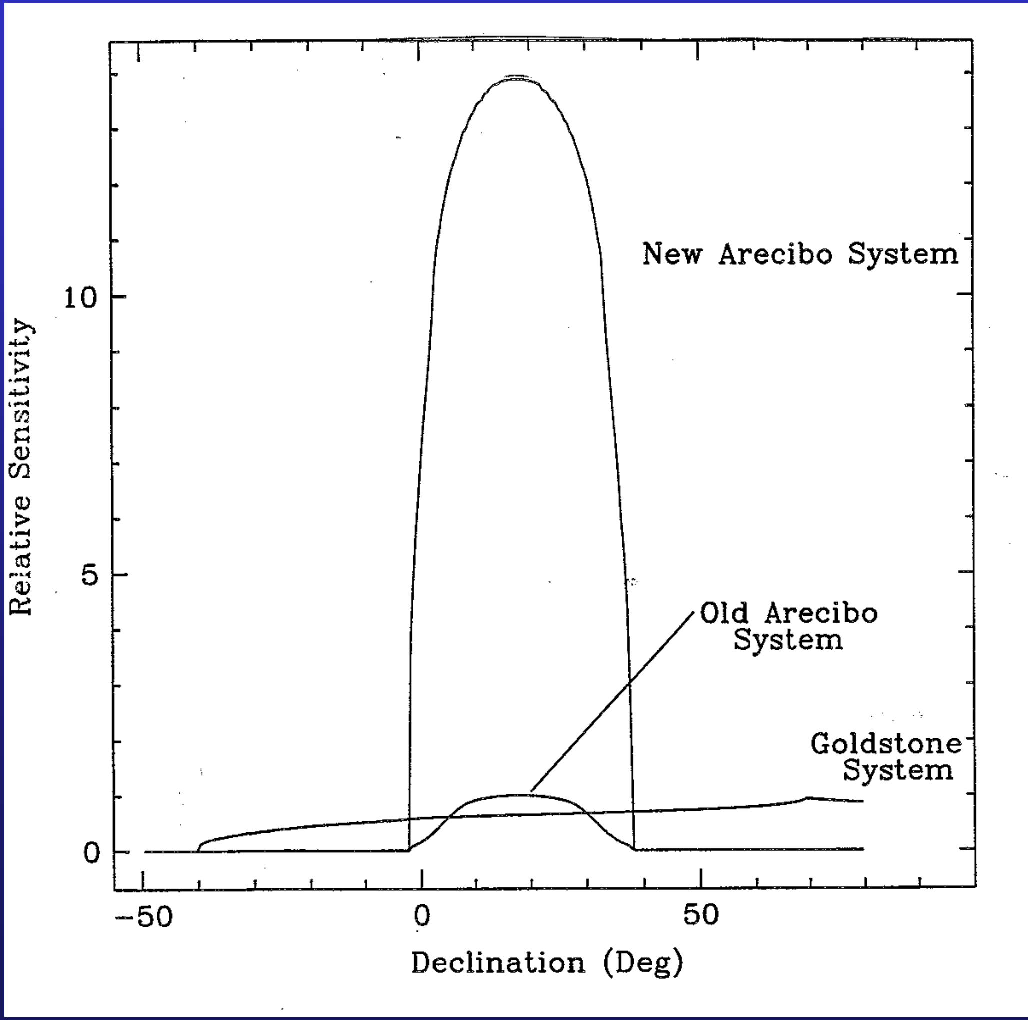
*** Gain = 4p x antenna effective area / ?^{2}**

ARECIBO 305m NSF
TELESCOPE
12.6cm, 1000kW TRANSMITTER

GOLDSTONE 70m
NASA DSN ANTENNA
MOJAVE DESERT
3.5cm, 450kW TX

PLANETARY RADAR ASTRONOMY

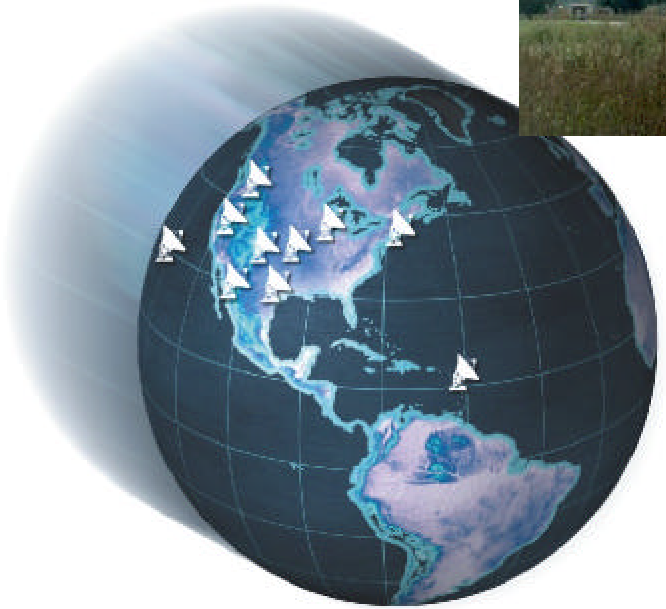
ARECIBO & GOLDSTONE RELATIVE SENSITIVITIES



ARECIBO

GOLDSTONE

VLBA



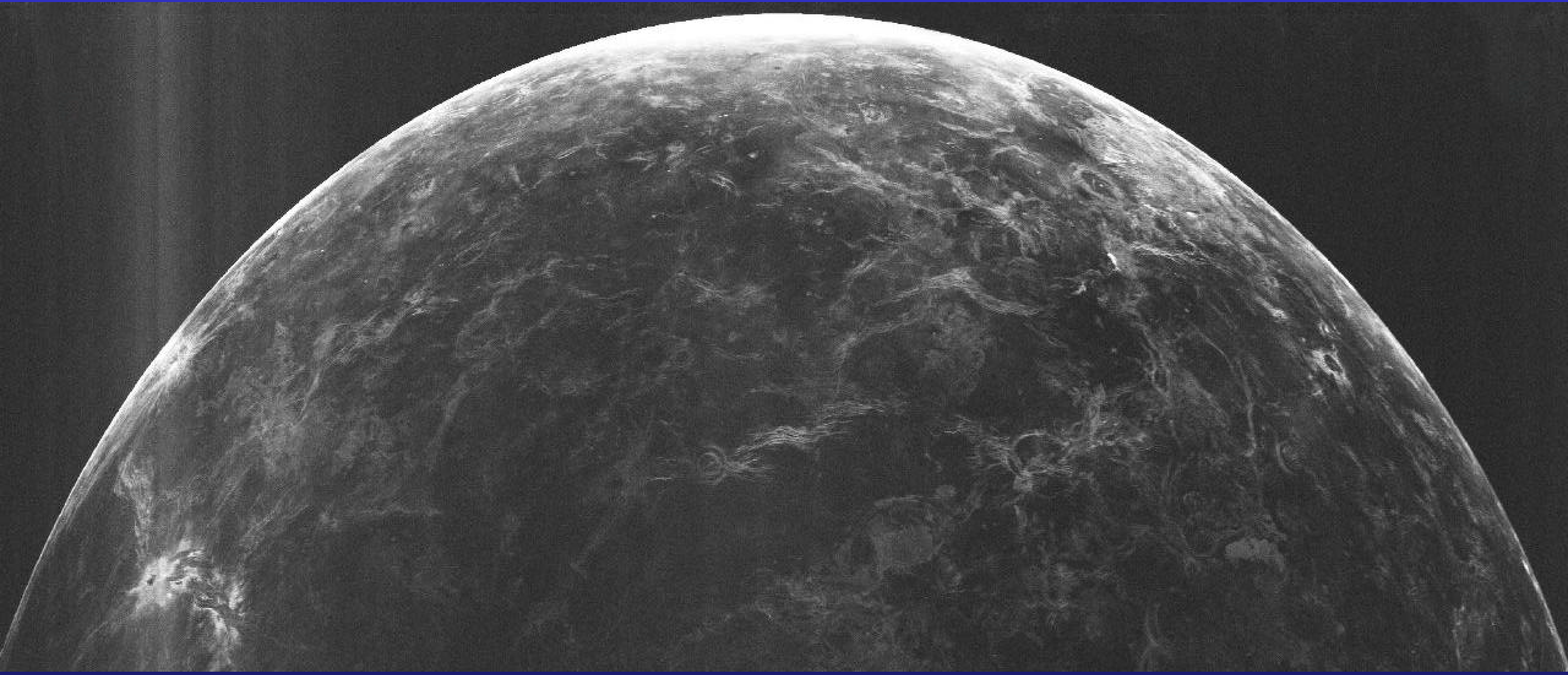
PLANETARY RADAR ASTRONOMY

OBSERVATIONAL GOALS

- **Near earth asteroids – shapes, sizes, densities, rotational properties**
- **Main belt asteroids – surface and rotational properties**
- **Comets – properties of the nuclei and comae**
- **Astronmetry on asteroids and comets**
- **Terrestrial planets – imaging, surface properties and spin vectors**
- **Outer planet satellites and rings – surface properties**

NAIC

The LUNAR SOUTH POLE 12.6 cm ARECIBO IMAGE
Courtesy of N. Stacy



Arecibo – GBT bistatic radar image of Venus

RADAR ASTRONOMY BASICS

Radar Equation:

Normalized Backscatter

Cross Section, the radar albedo

Transmitting Antenna Gain $4\pi A_t/\lambda^2$

Average Transmitter Power

Target Area

Integration time

$$\textbf{Detectability} \propto \frac{Tx \,.\, Gt \,.\, Ar \,.\, s_o \,.\, A}{R^4 \,.\, T_{sys}} \left[\frac{t}{B}\right]^{1/2}$$

Distance

Receive Antenna Collecting Area

System Temperature

Rotational Doppler Broadening $\propto \lambda^{-1}$

PLANETARY RADAR ASTRONOMY

OBSERVATIONS

- Transmit a mono-chromatic continuous wave (CW)

  Objectives: The echo power spectrum – the one dimensional distribution of echo power as a function of the rotational Doppler shift.

  The Doppler shift (i.e. radial velocity) of the center-of-mass of the object for orbit determination

- Transmit a signal with modulation in time – pulses or phase encoding

  Objectives: Two dimensional distribution of echo power – function of rotational Doppler shift and distance (delay-Doppler mapping). Full polarization Stokes' parameter imaging.

  Distance and velocity of center-of -mass

PLANETARY RADAR ASTRONOMY

- Normally transmit circularly polarized signal

- Receive the echo in both senses of circular polarization

  Echo power in the OC (Opposite Circular to that transmitted) sense
  => mirror like reflection

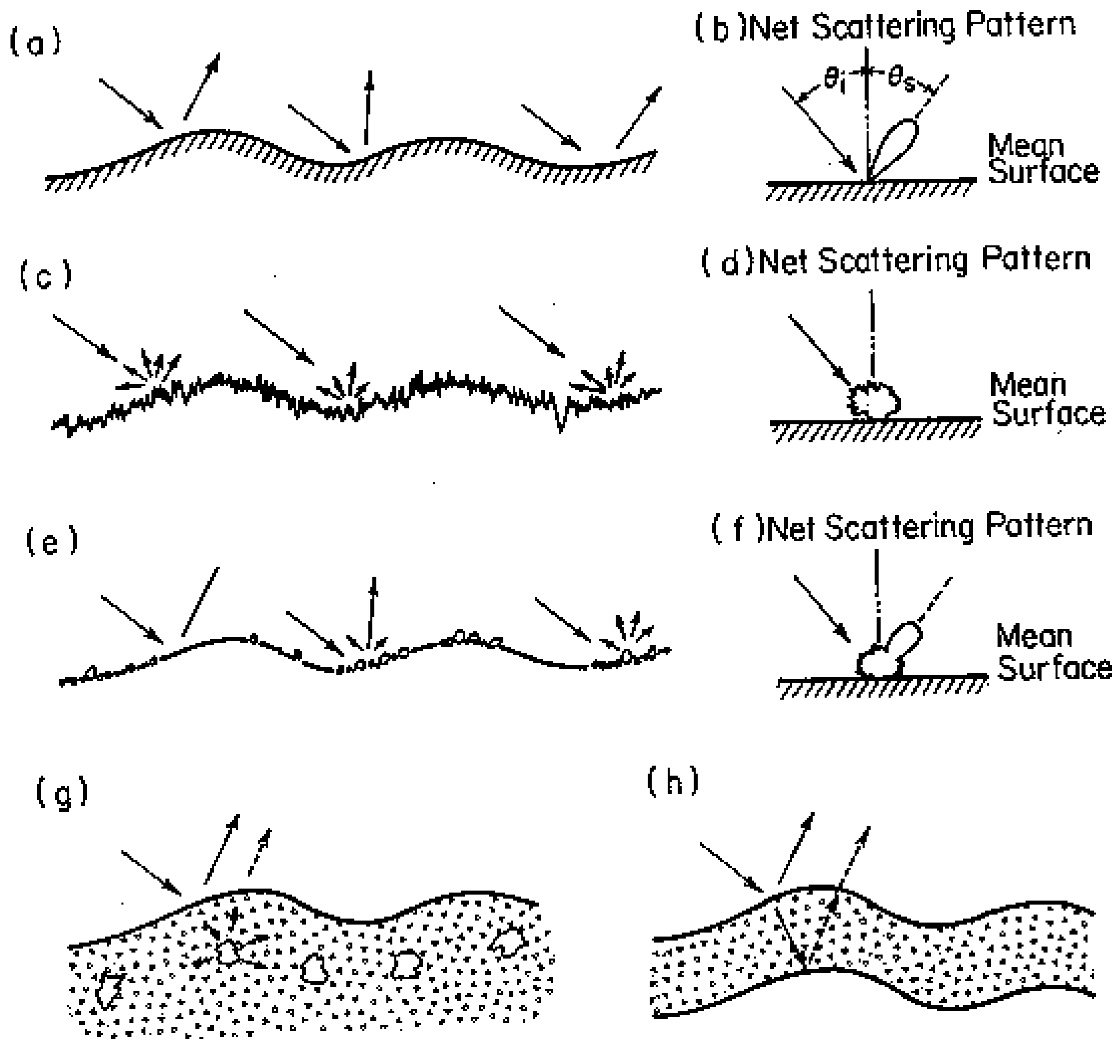
  Echo power in the SC (Same Circular as that transmitted) sense
  => multiply scattered power, scattering from sharp edges, etc

- Form circular polarization ratios (m_c)
  $m_c = s_{sc} / s_{oc}$ => measure of surface roughness (except ice)

  where

  s_{sc} = cross section in the SC sense of circular polarization

  s_{oc} = cross section in the OC sense of circular polarization


(a)
(b) Net Scattering Pattern
θ_i
θ_s
Mean Surface
(c)
(d) Net Scattering Pattern
Mean Surface
(e)
(f) Net Scattering Pattern
Mean Surface
(g)
(h)

PLANETARY RADAR ASTRONOMY

FOR A DIELECTRIC SPHERE SMOOTH AT ? SCALES

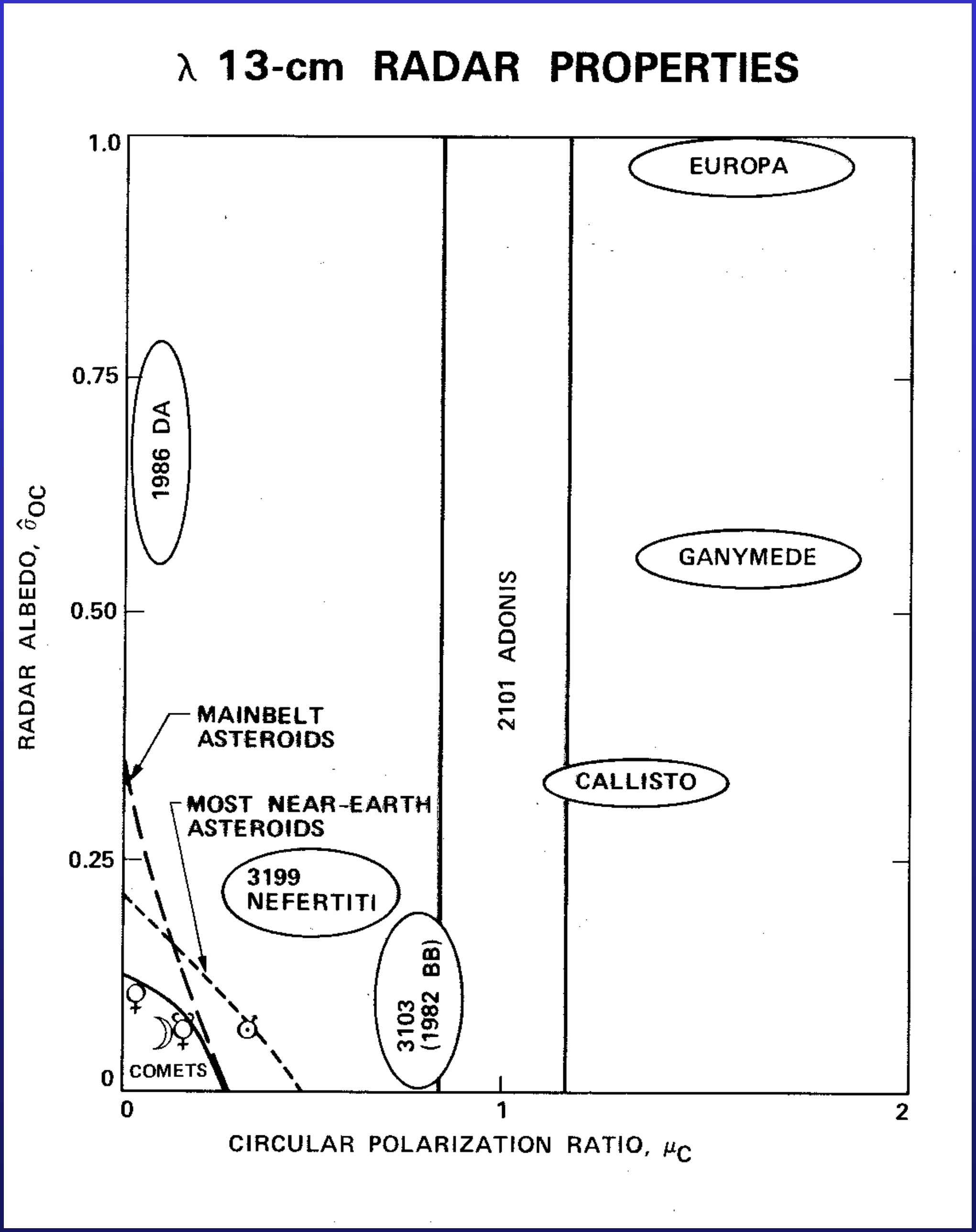
SPECULAR ECHO POWER => CROSS SECTION (radar albedo)

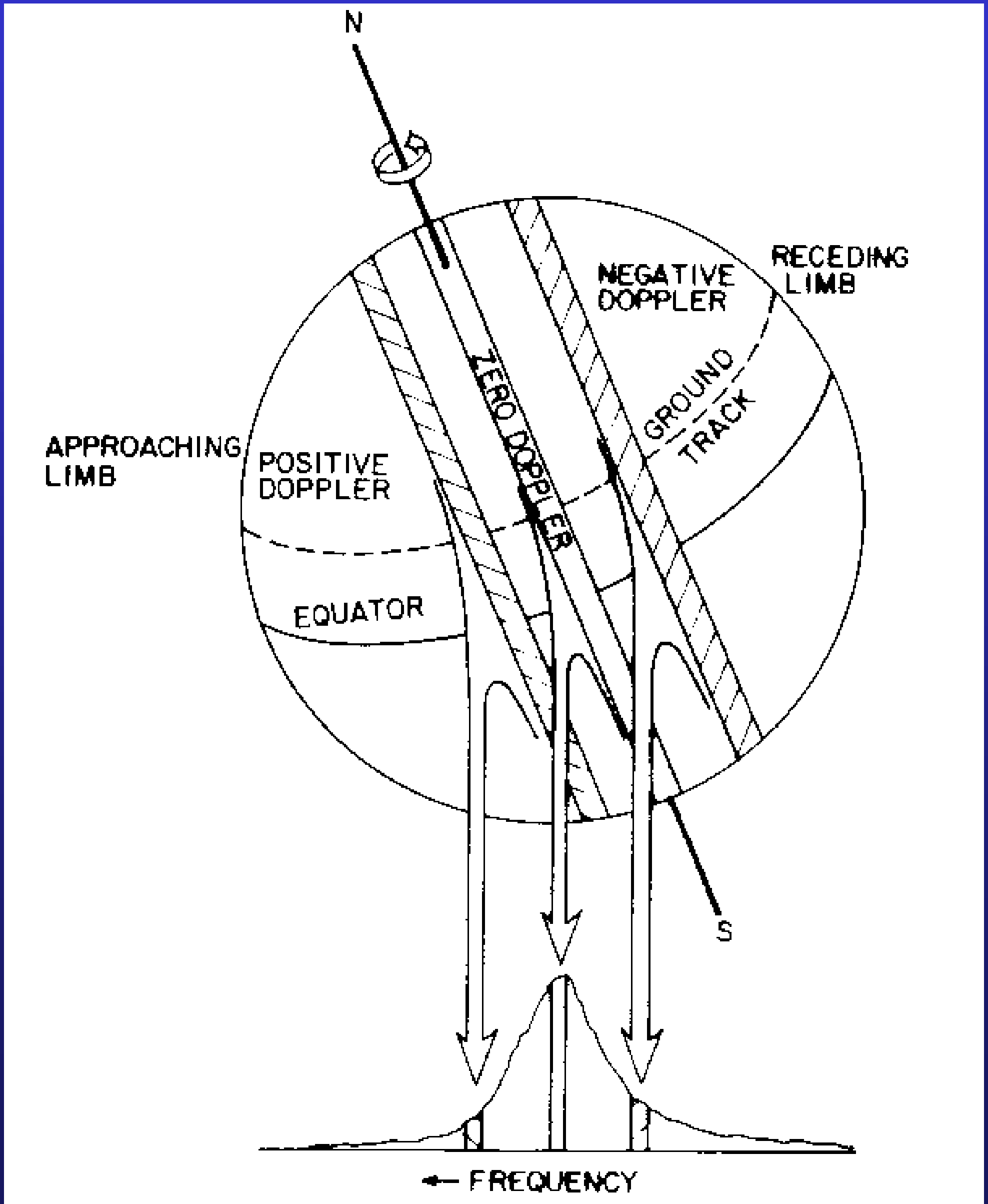
~ FRESNEL REFLECTIVITY

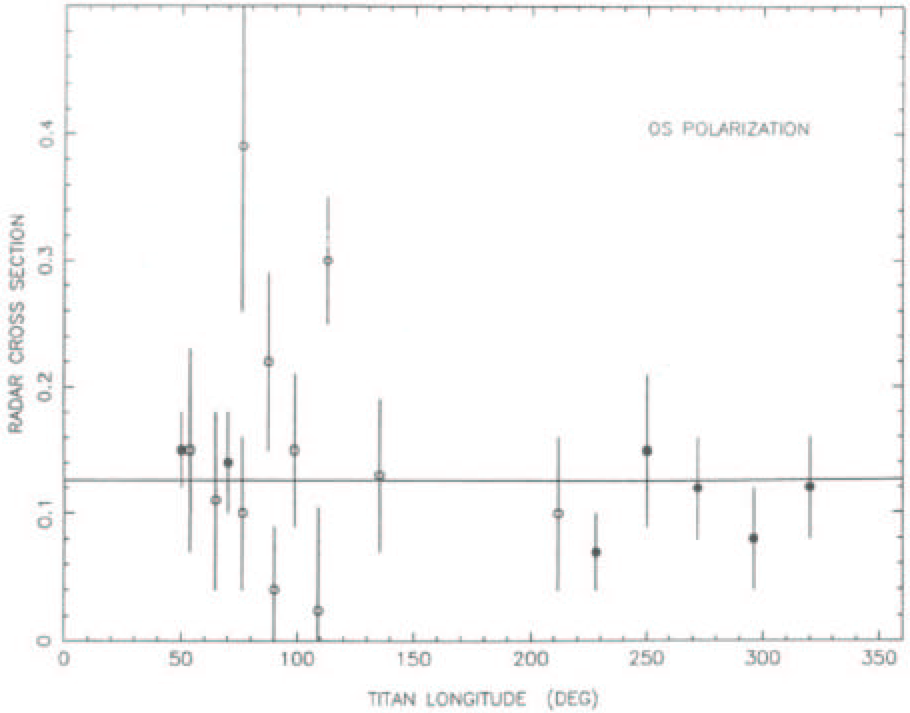
FRESNEL REFLECTIVITY = $[(e^{1/2} - 1)/(e^{1/2} + 1)]^2$, e = dielectric const.

e is dependent on surface composition (e.g. rock type) or, for low density surfaces such as the lunar regolith, the porosity of the surface

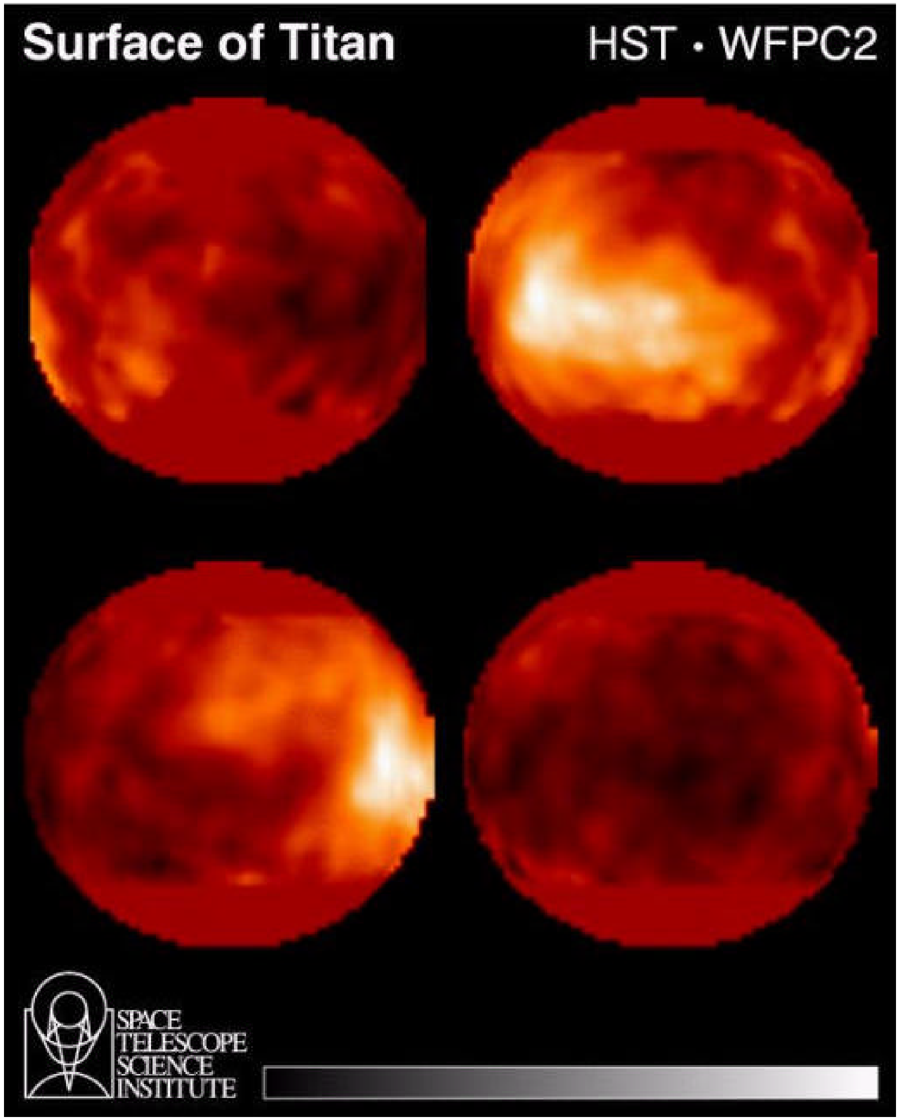
SPECULAR ECHO DOPPLER BROADENING => RMS SLOPE


λ 13-cm RADAR PROPERTIES
RADAR ALBEDO, $\hat{\sigma}_{OC}$
CIRCULAR POLARIZATION RATIO, μ_C
1.0
0.75
0.50
0.25
0
0
1
2
EUROPA
GANYMEDE
CALLISTO
1986 DA
2101 ADONIS
MAINBELT ASTEROIDS
MOST NEAR-EARTH ASTEROIDS
3199 NEFERTITI
3103 (1982 BB)
COMETS


N
NEGATIVE DOPPLER
RECEDING LIMB
ZERO DOPPLER
GROUND TRACK
APPROACHING LIMB
POSITIVE DOPPLER
EQUATOR
S
FREQUENCY



Goldstone – VLA radar observations
of Titan (Muhleman et al, 1993)



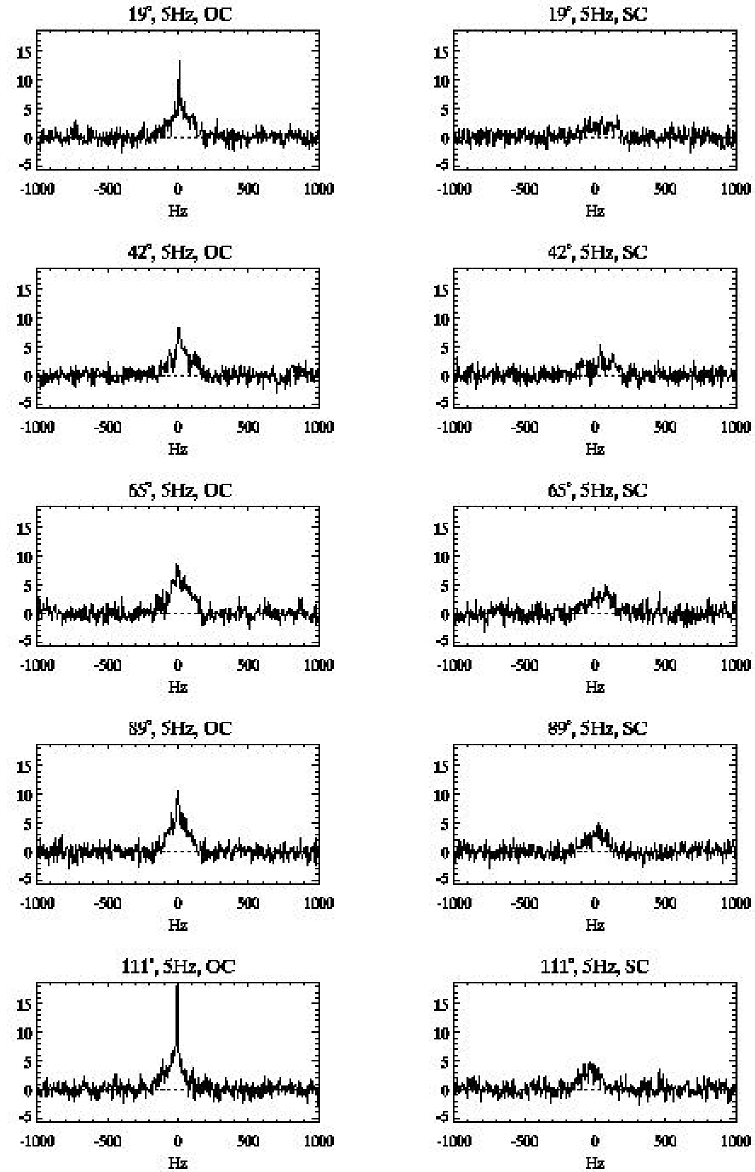
Arecibo radar echo spectra for five sub-earth longitudes on Titan

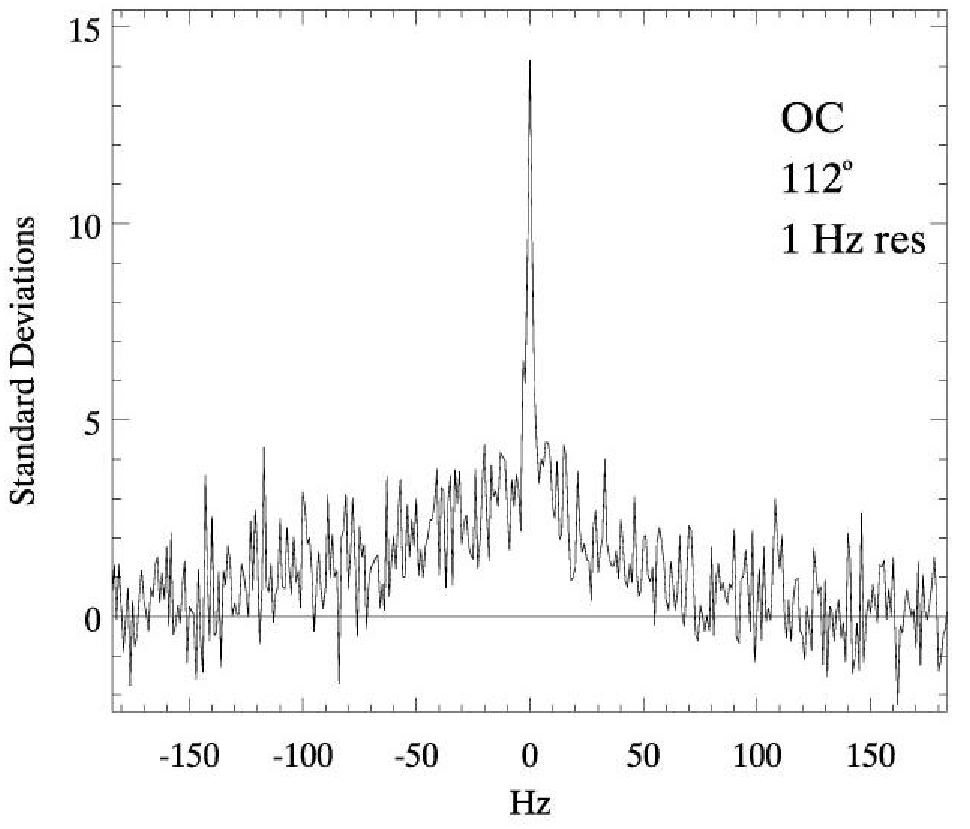
Narrow specular spikes at 15 deg and 111 deg are indicative of very smooth surfaces

Titan's Doppler bandwidth at 12.6 cm is 325 Hz.

OC – Sense of receive polarization corresponding to reflection from a mirror like surface.

SC – Depolarized sense, indicative of small scale surface roughness.





Smooth (at wavelength scales) solid surface or liquid surface?

RADAR REFLECTION PROPERTIES OF LIQUID HYDROCARBON "LAKES" ON TITAN

OC SPECULAR ECHO FROM THE SUB-EARTH LOCATION

LIQUID CH_4 – C_2H_6 – N_2 MIXTURE AT 94K HAS

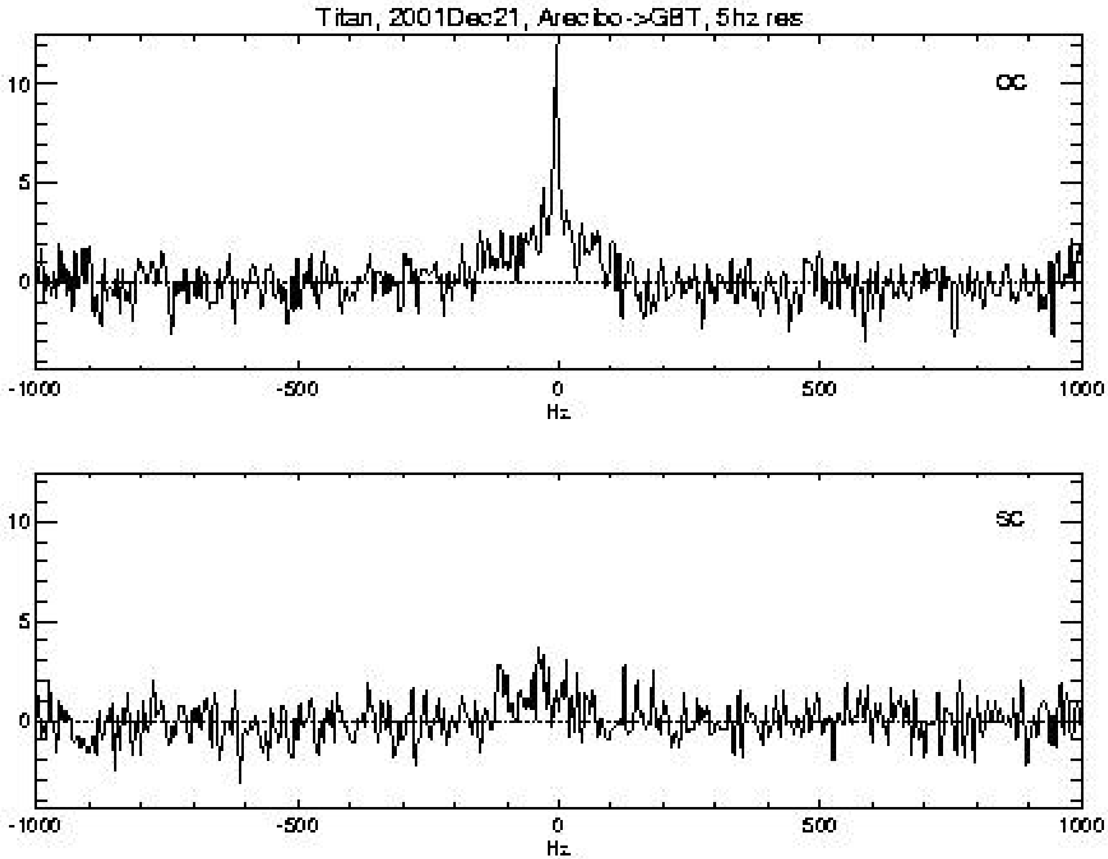
1.65 < DIELECTRIC CONST < 1.81 (Thompson&Squyres)

=> RADAR CROSS SECTIONS < 0.022

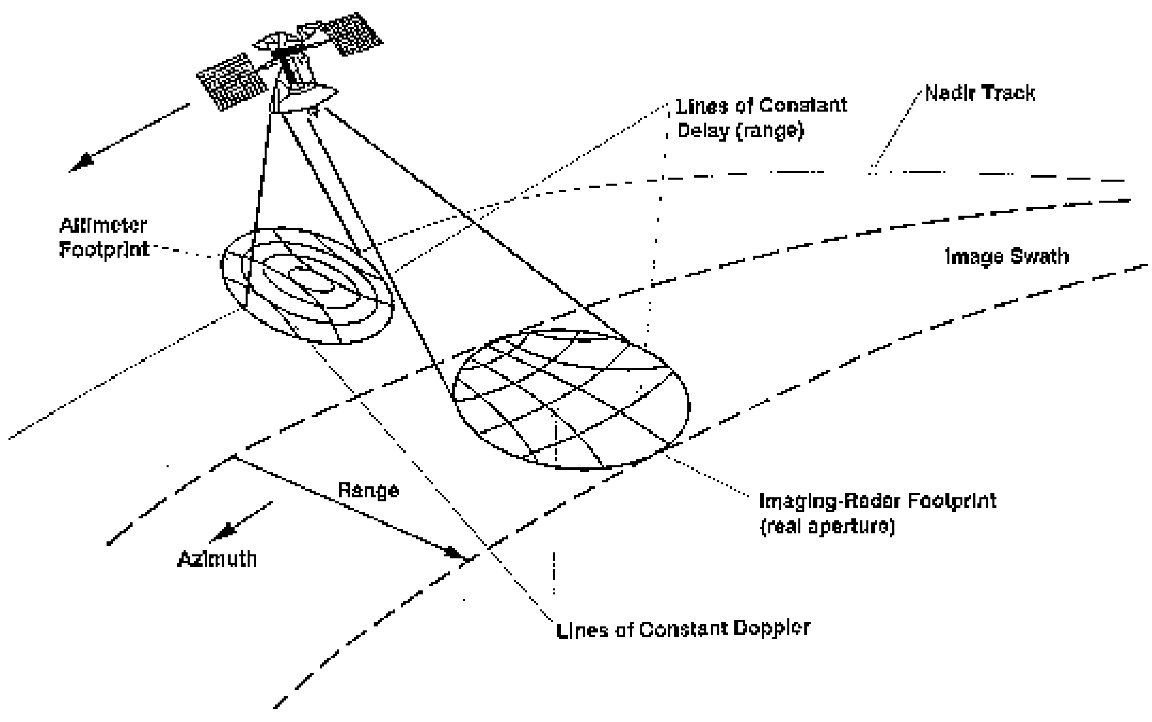
(addition of other constituents could raise the dielectric constant)

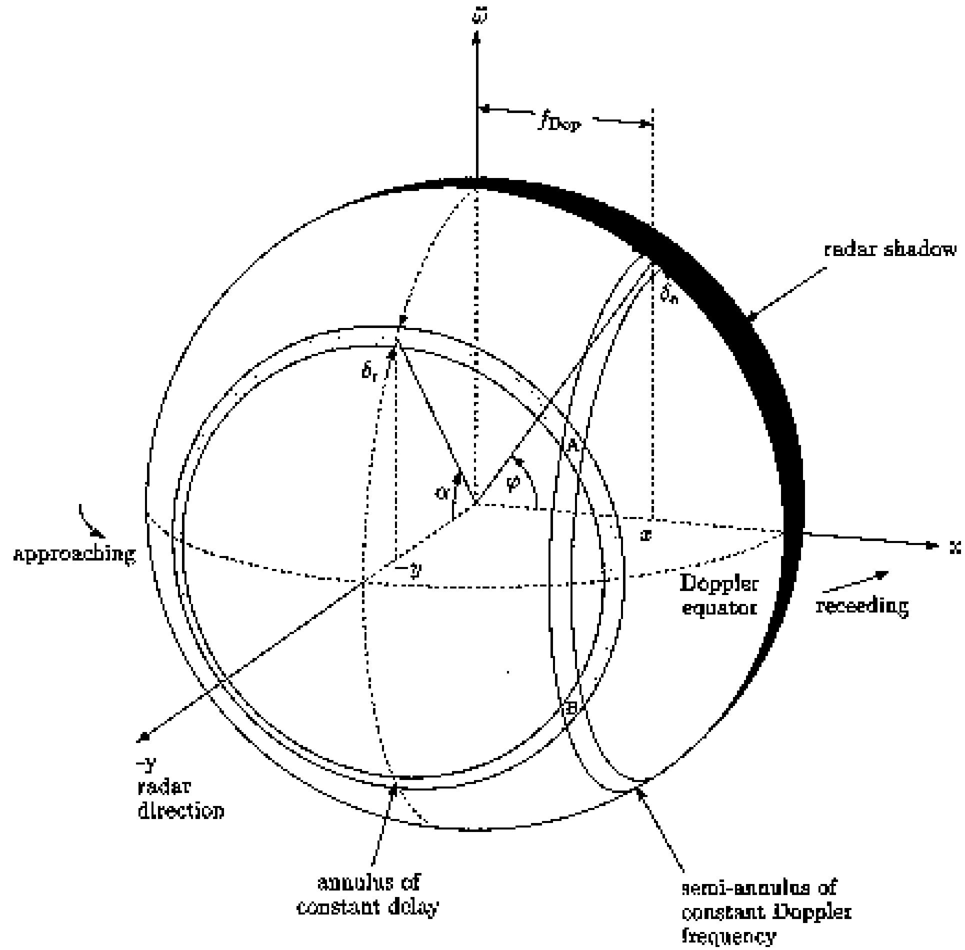
DOPPLER BROADENING CONSISTENT WITH MAXIMUM EXPECTED WIND DRIVEN WAVE SLOPES

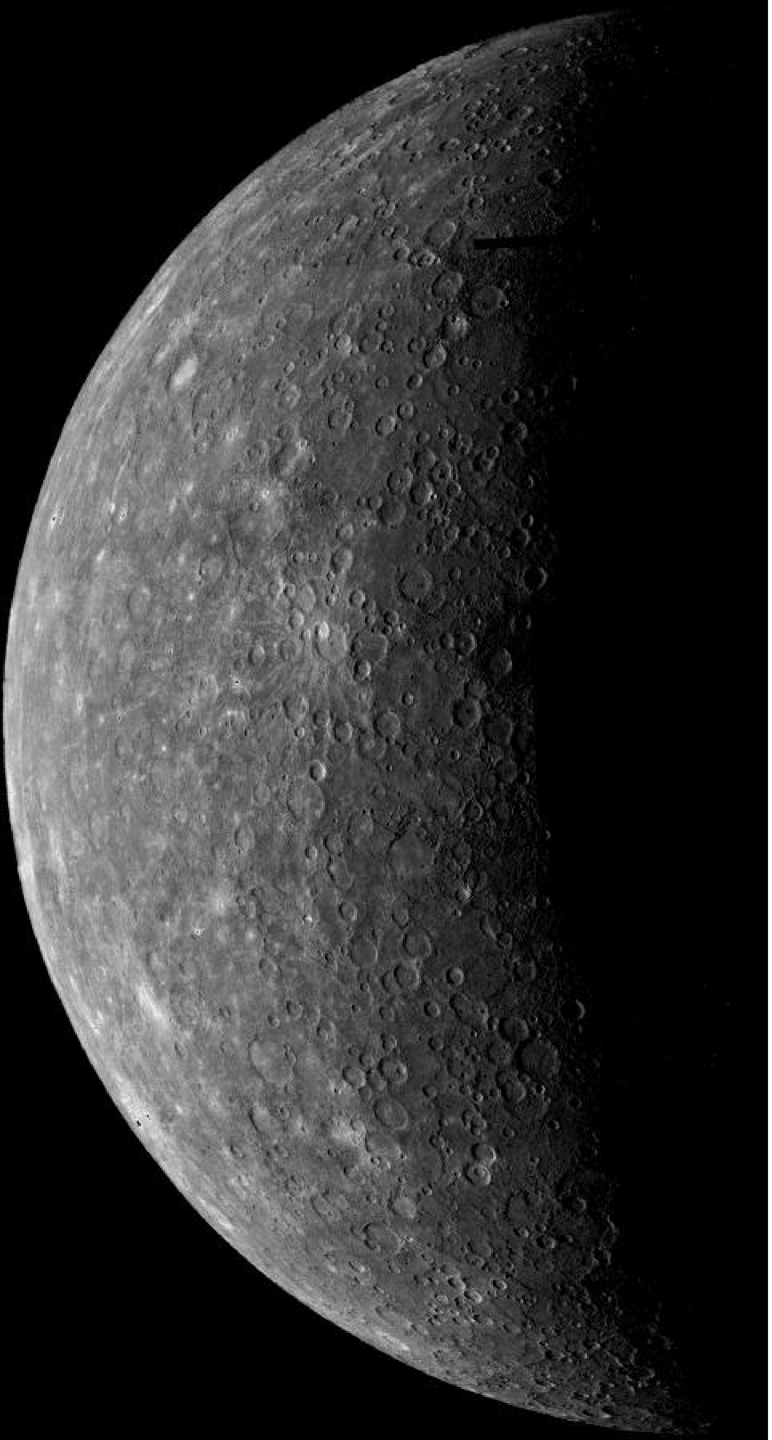
(0.3 m/sec winds over fetches of > few km will induce waves with maximum slope of 11^0 (Ghafoor et al, 2000))

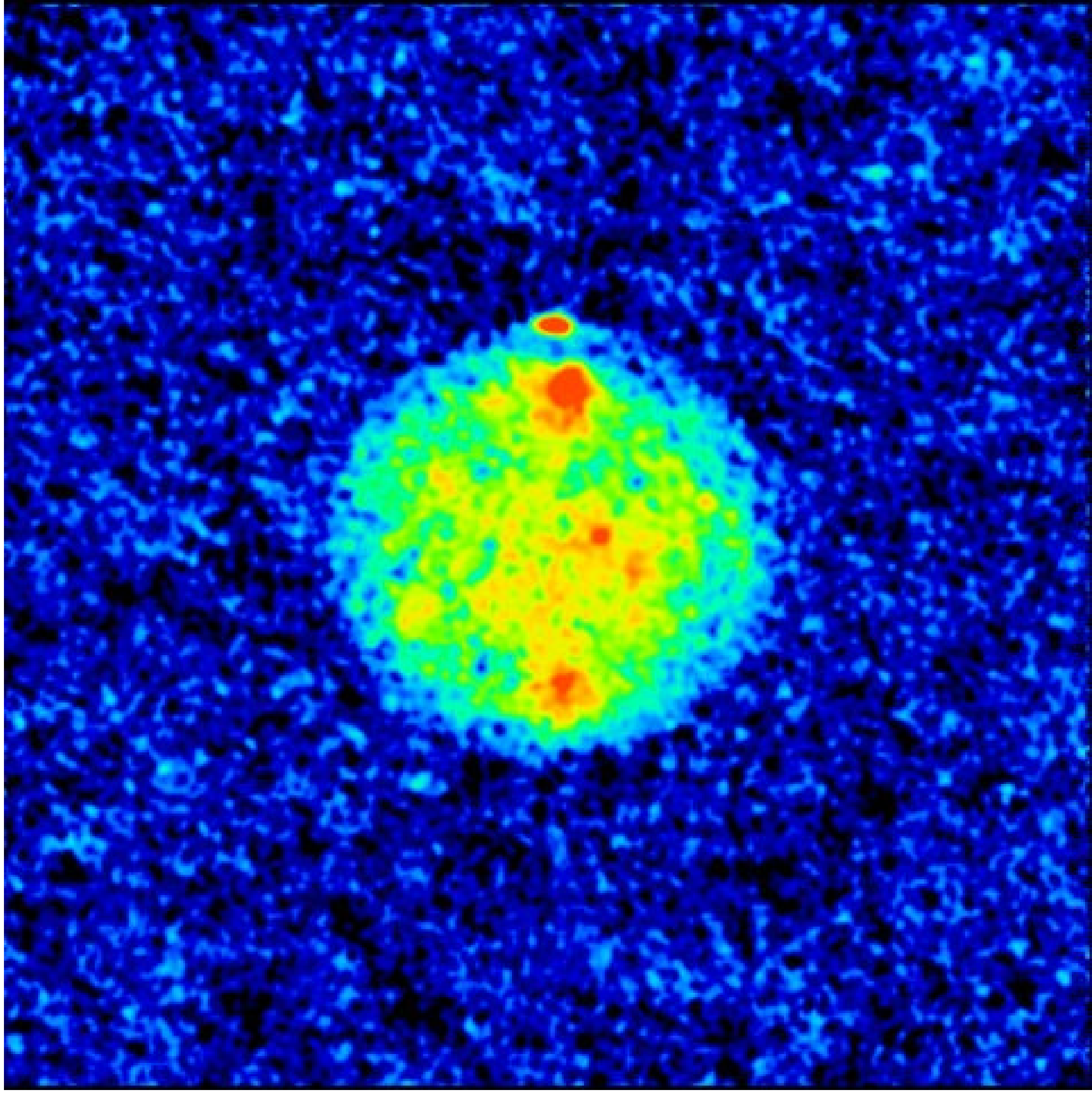


Arecibo – GBT Titan OC and SC spectra
sub-earth longitude of 112 deg


Lines of Constant
Delay (range)
Nadir Track
Altimeter
Footprint
Image Swath
Range
Imaging-Radar Footprint
(real aperture)
Azimuth
Lines of Constant Doppler

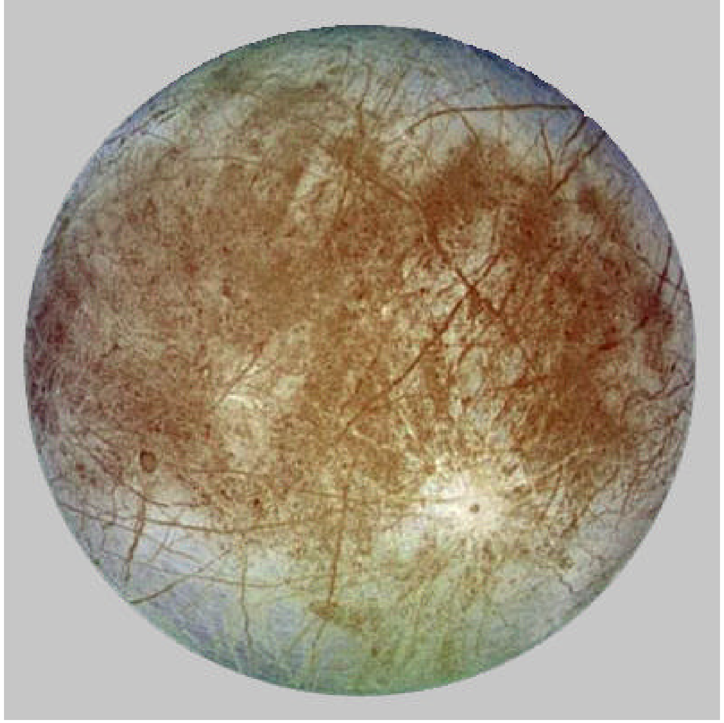

z
f_{Dop}
radar shadow
δ_n
δ_r
A
α
φ
x
approaching
$-y$
x
Doppler
equator
receeding
B
-y
radar
direction
annulus of
constant delay
semi-annulus of
constant Doppler
frequency

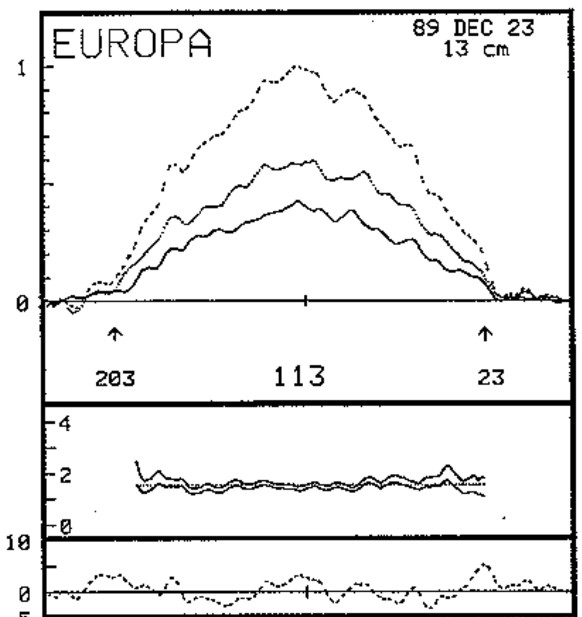


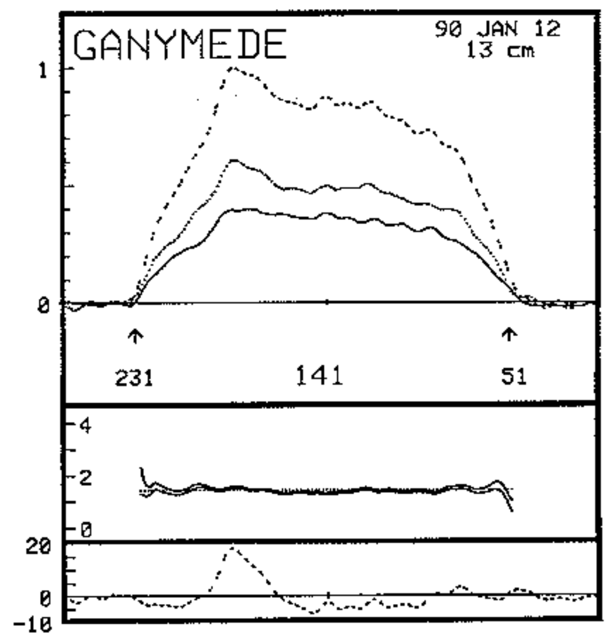


Mercury from
Mariner 10, 1974

Goldstone – VLA
radar image at 3.5 cm
Butler et al




EUROPA
89 DEC 23
13 cm
1
0
203
113
23
4
2
0
10
0
-5


GANYMEDE
90 JAN 12
13 cm
1
0
231
141
51
4
2
0
20
0
-10

PLANETARY RADAR ASTRONOMY

Radar Properties of Icy Surfaces

- **High backscatter cross sections (s); unity or greater**

- **Circular polarization ratios (m_c) greater than unity**

$$m_c = s_{sc} / s_{oc}$$

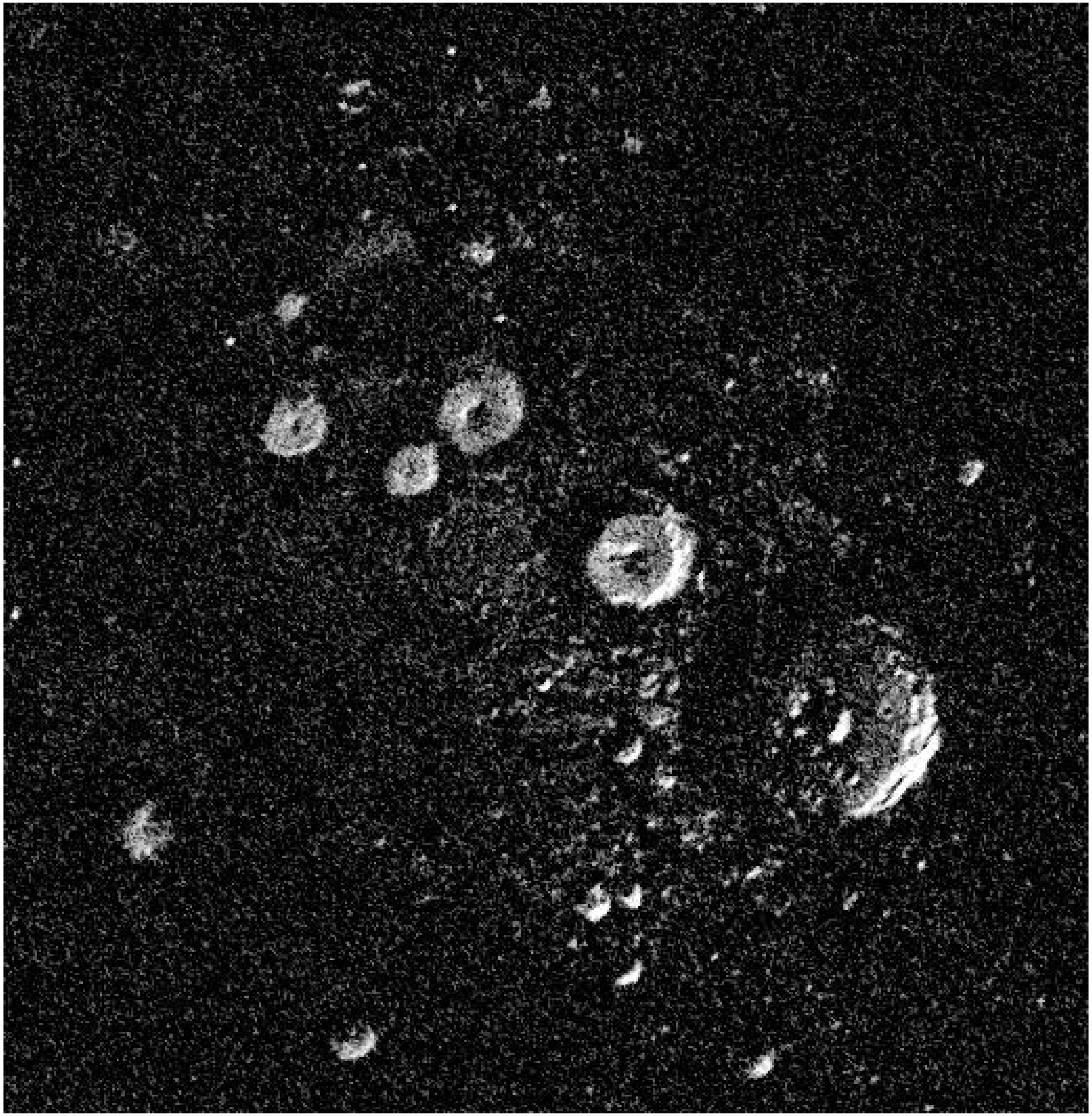
where

s_{sc} = cross section in the same sense of circular polarization as that transmitted

s_{oc} = cross section in the opposite sense of circular polarization – the sense expected for a mirror-like reflection

Arecibo radar image of the north pole of Mercury at 1.5 km resolution.

Image is 400 x 400 km (Harmon et al, 2001)



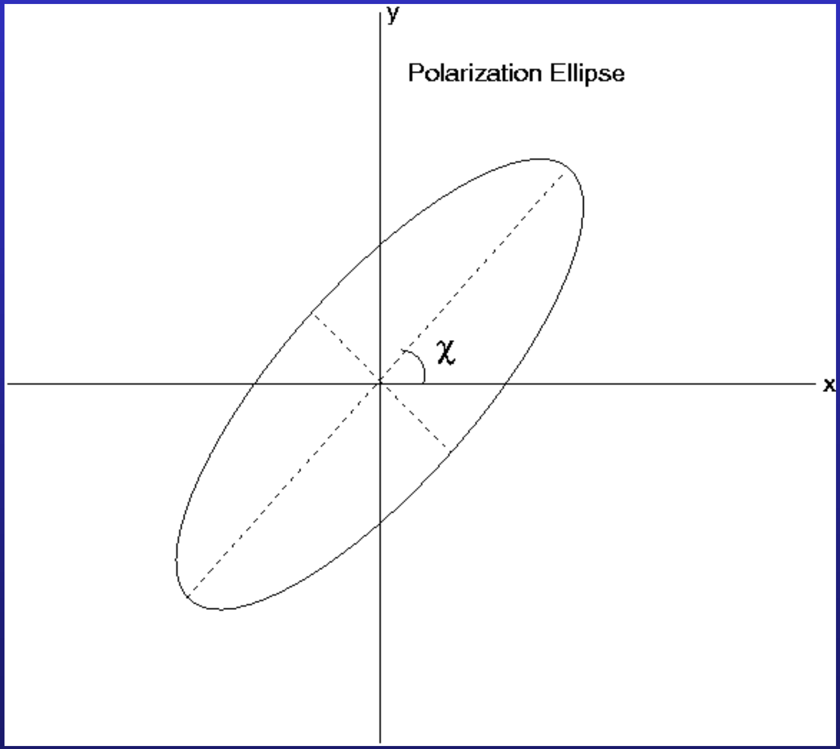
The LUNAR SOUTH POLE 12.6 cm ARECIBO IMAGE
Courtesy of N. Stacy

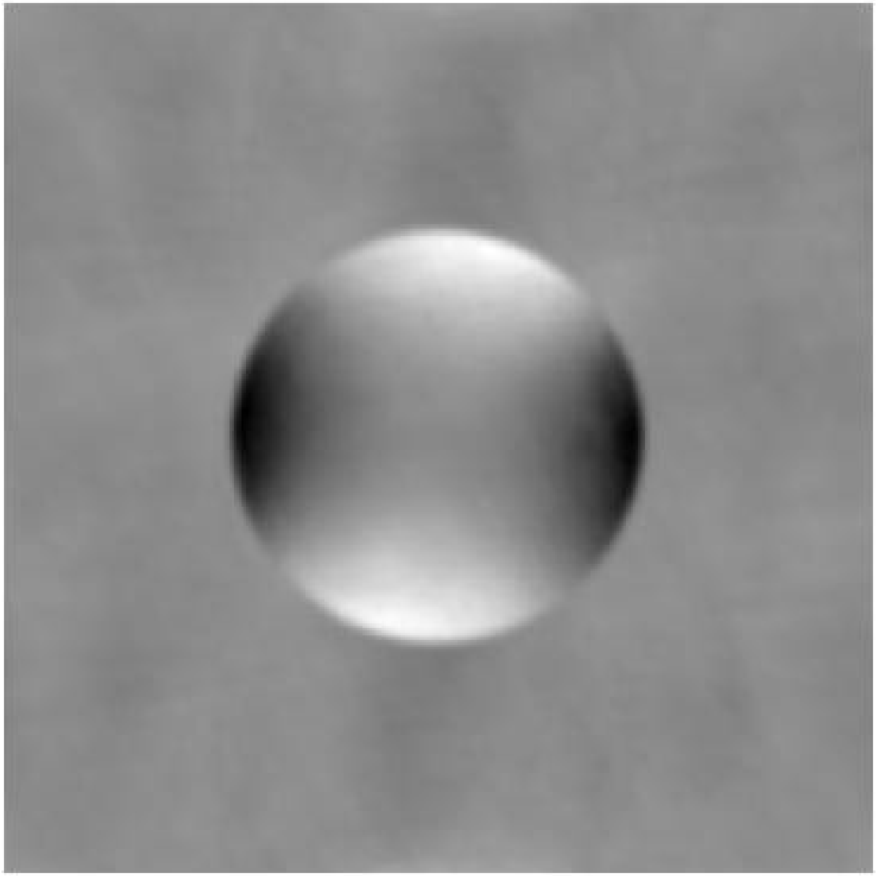
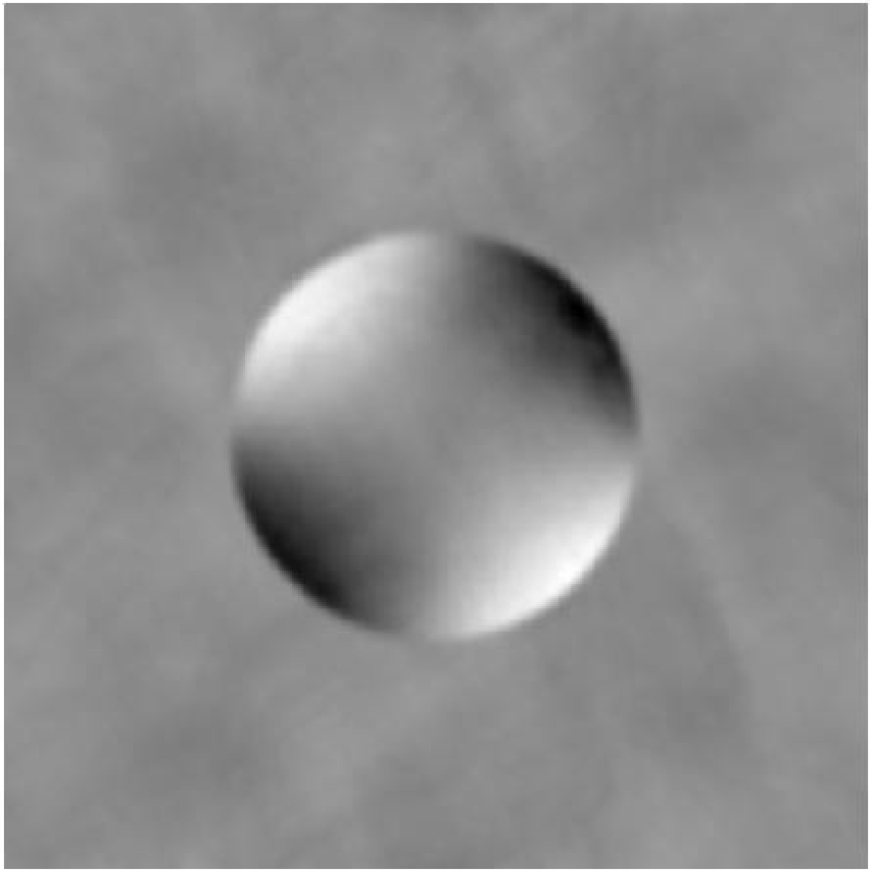
Stokes' Parameters

$$S = \begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \end{bmatrix} = \begin{bmatrix} \langle |?_{\mathrm{L}}|^2 \rangle + \langle |?_{\mathrm{R}}|^2 \rangle \\ 2\,\mathrm{Re}\langle ?_{\mathrm{L}} ?^*_{\mathrm{R}} \rangle \\ 2\,\mathrm{Im}\langle ?_{\mathrm{L}} ?^*_{\mathrm{R}} \rangle \\ \langle |?_{\mathrm{L}}|^2 \rangle - \langle |?_{\mathrm{R}}|^2 \rangle \end{bmatrix}$$

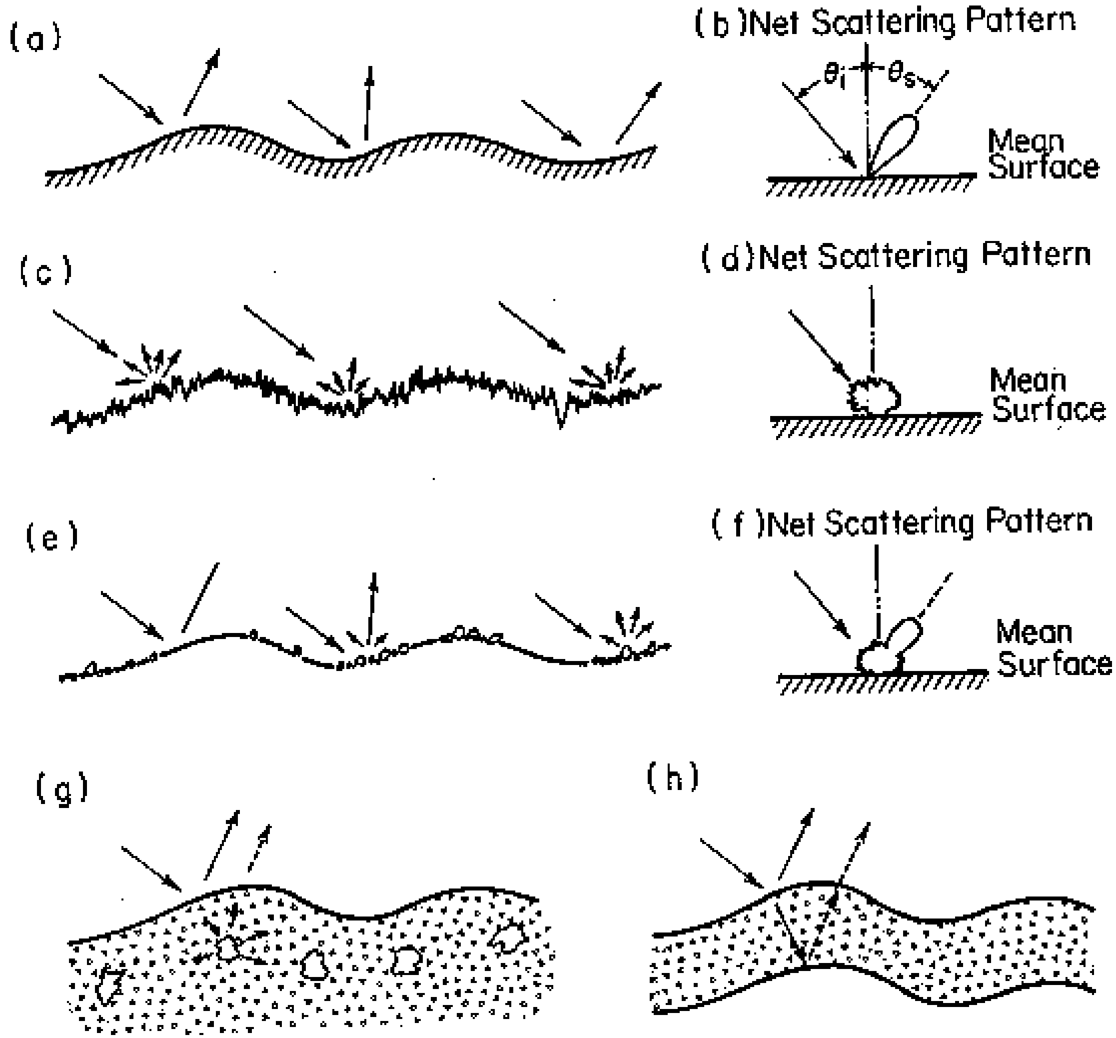
$$m = \frac{\sqrt{S_2^2 + S_3^2}}{S_1}$$

$$c = \frac{1}{2}\,\mathrm{Arctan}\left(\frac{S_3}{S_2}\right)$$

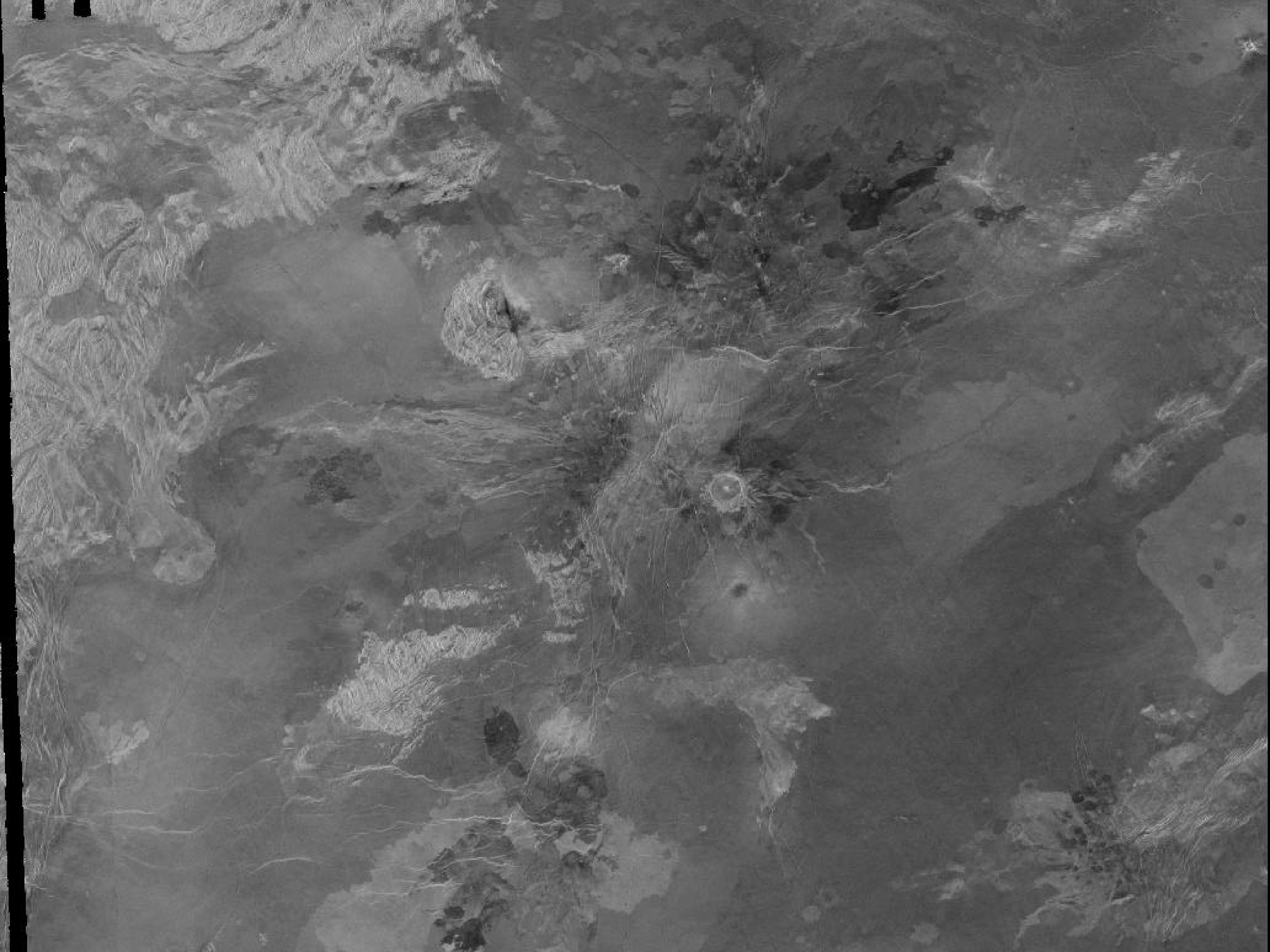


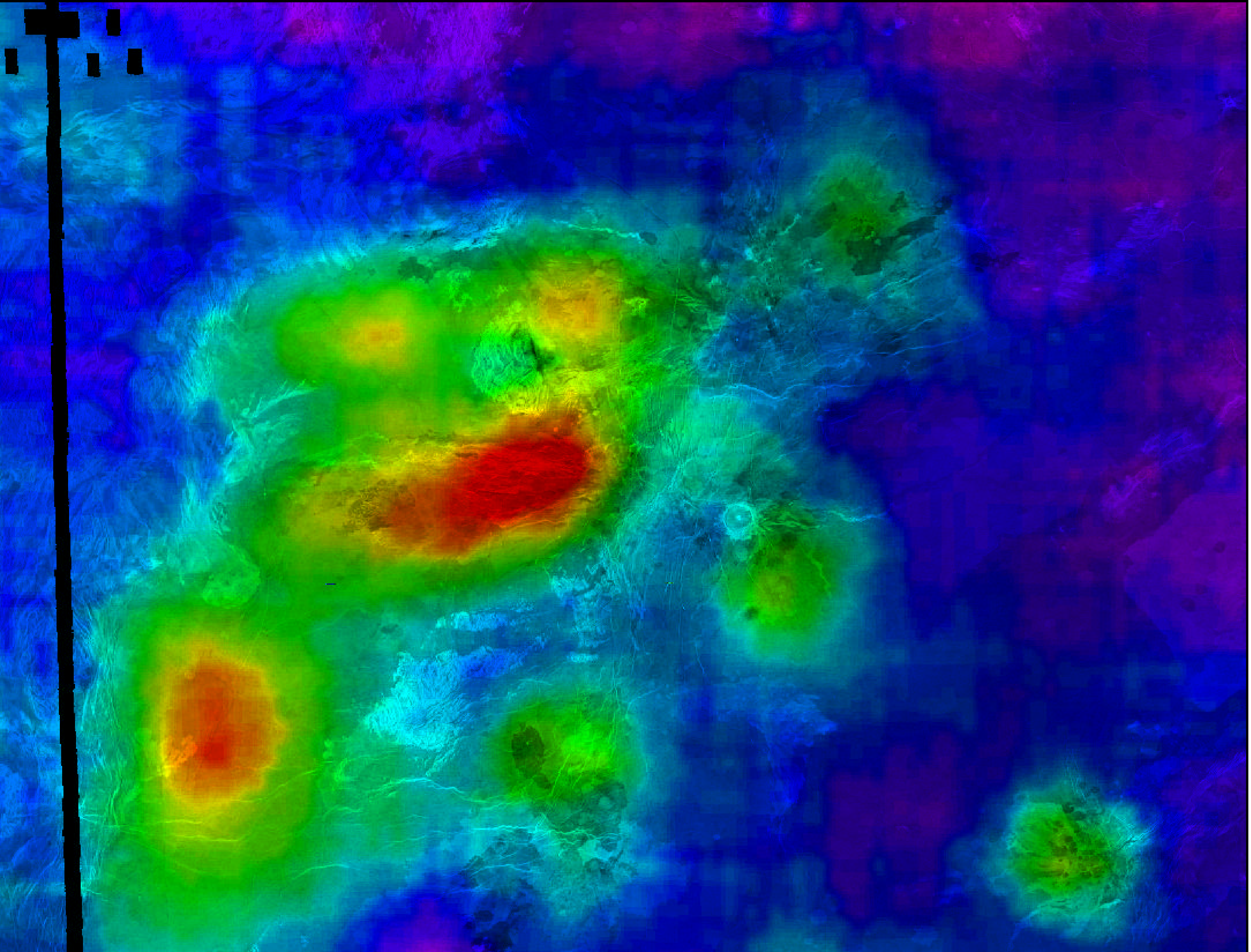


VLA images of the 21 cm wavelength thermal emission from the Moon in the two linear polarization Stokes' parameters Q and U. (J-L Margot and D.B. Campbell)

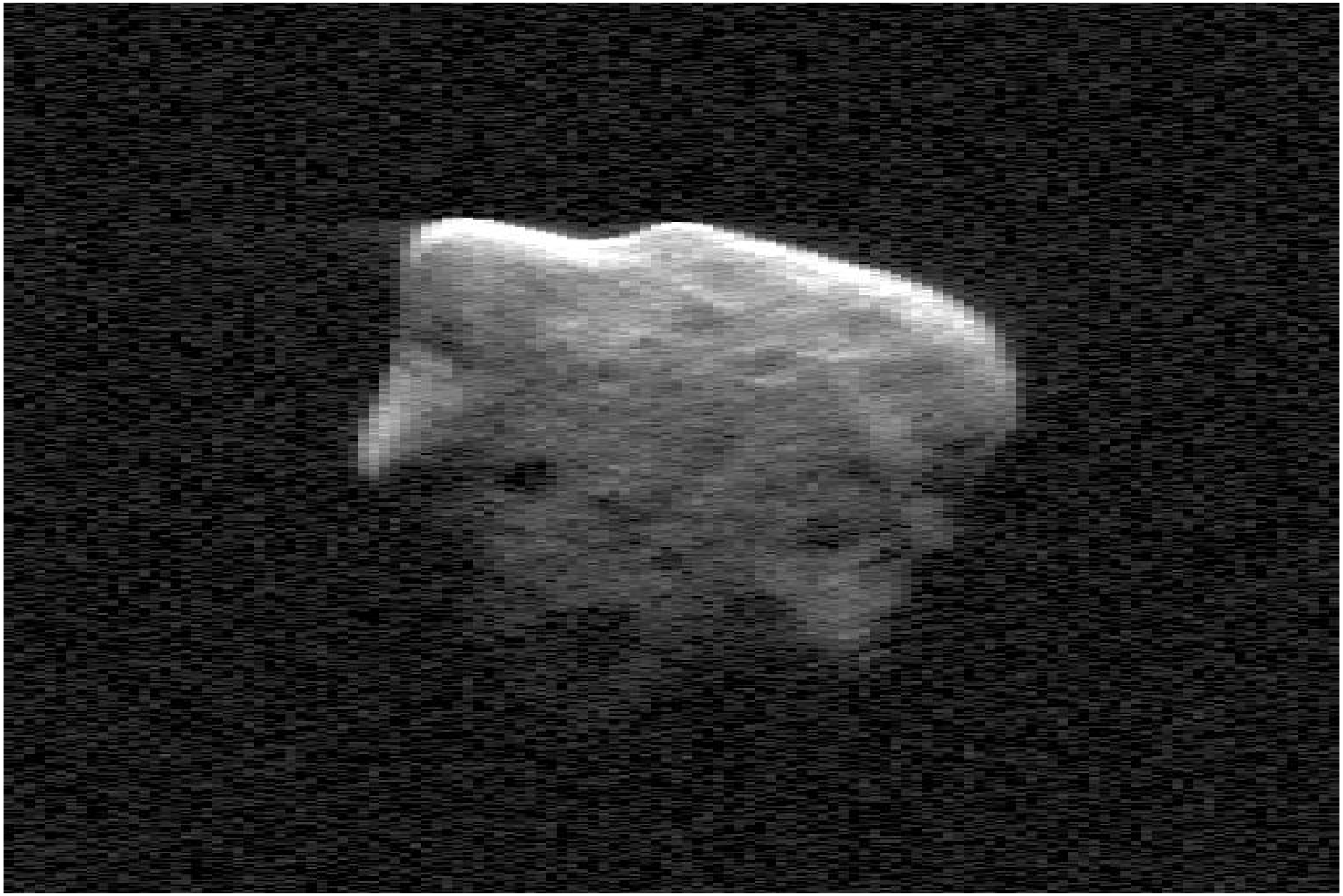


(a)
(b) Net Scattering Pattern
θi
θs
Mean Surface
(c)
(d) Net Scattering Pattern
Mean Surface
(e)
(f) Net Scattering Pattern
Mean Surface
(g)
(h)



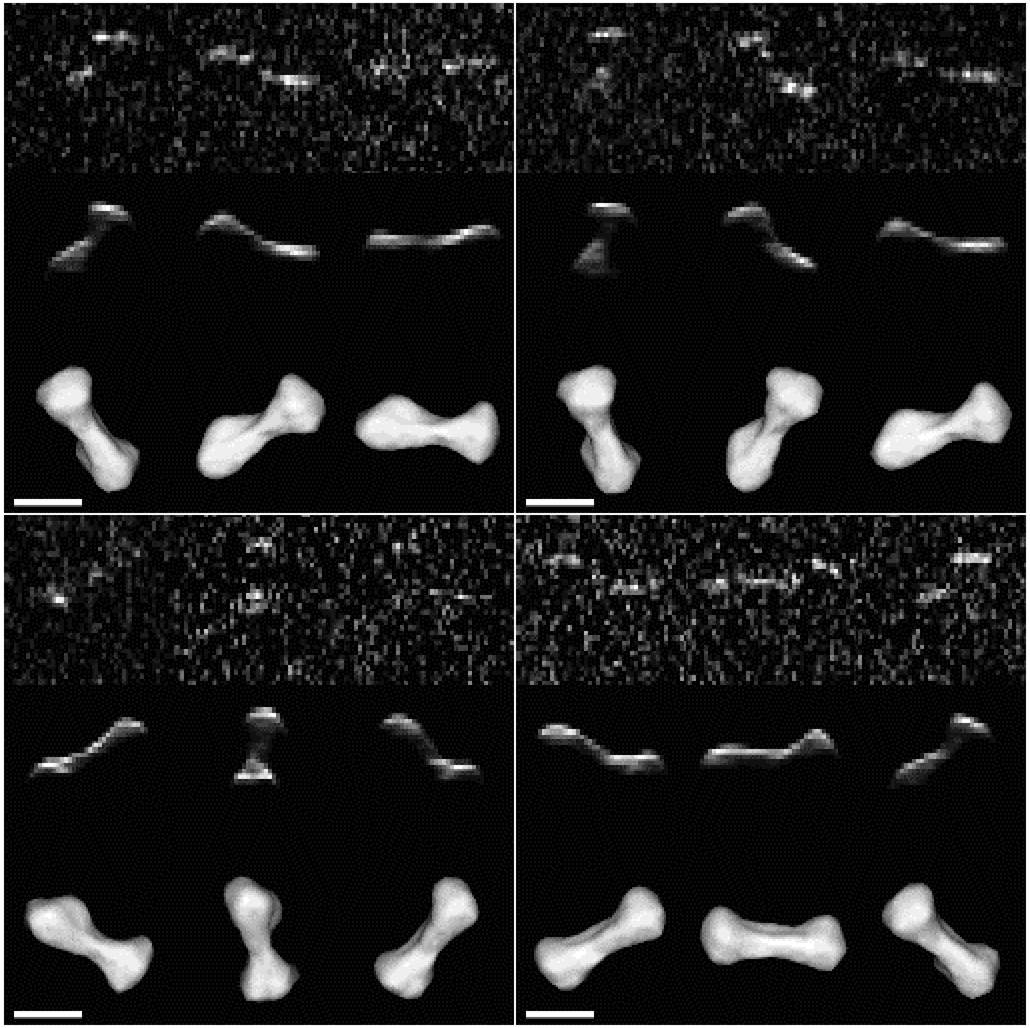


Mainbelt asteroid Gaspra
from the Galileo spacecraft



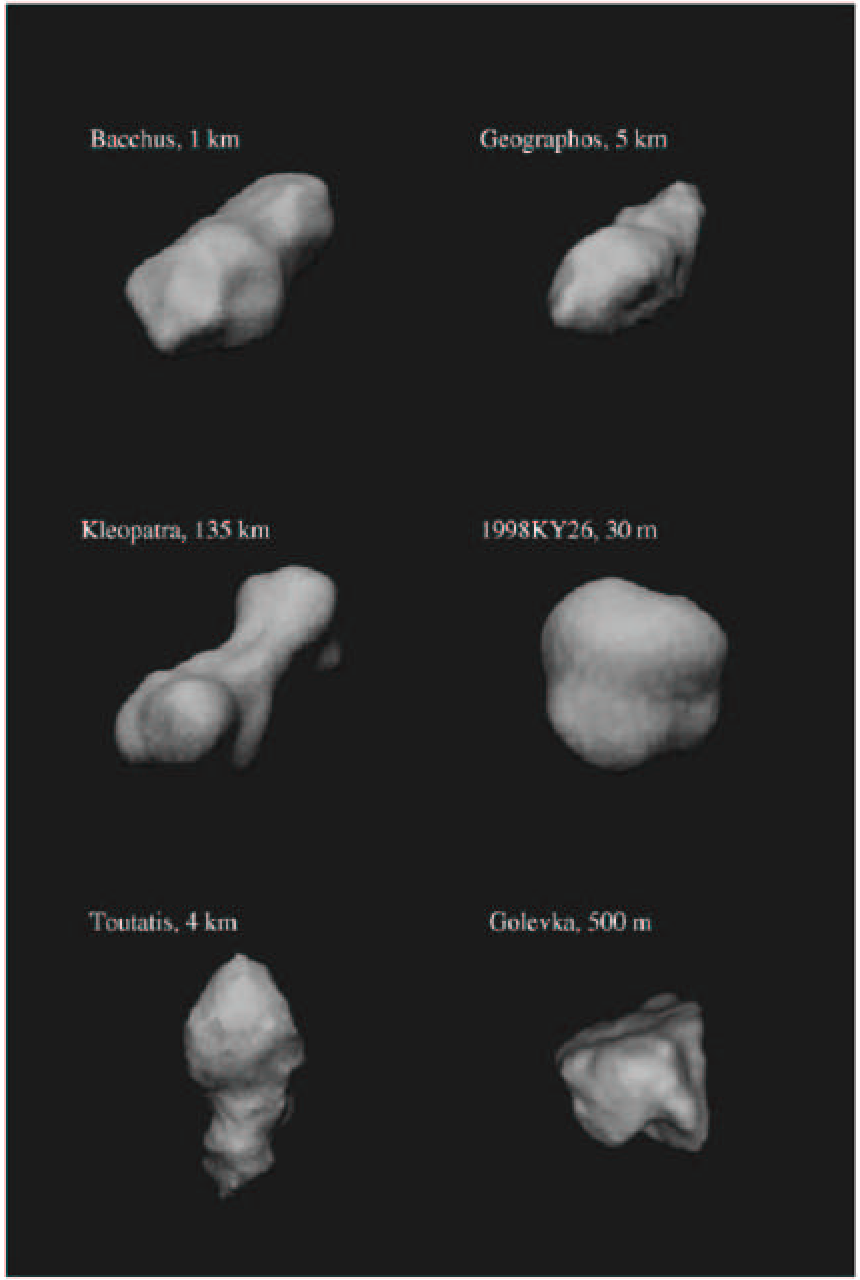
Arecibo radar image of the near earth asteroid 1999 JM8 at 15 m resolution

Arecibo radar image of the near earth asteroid 2002 NY40 at 10 m resolution



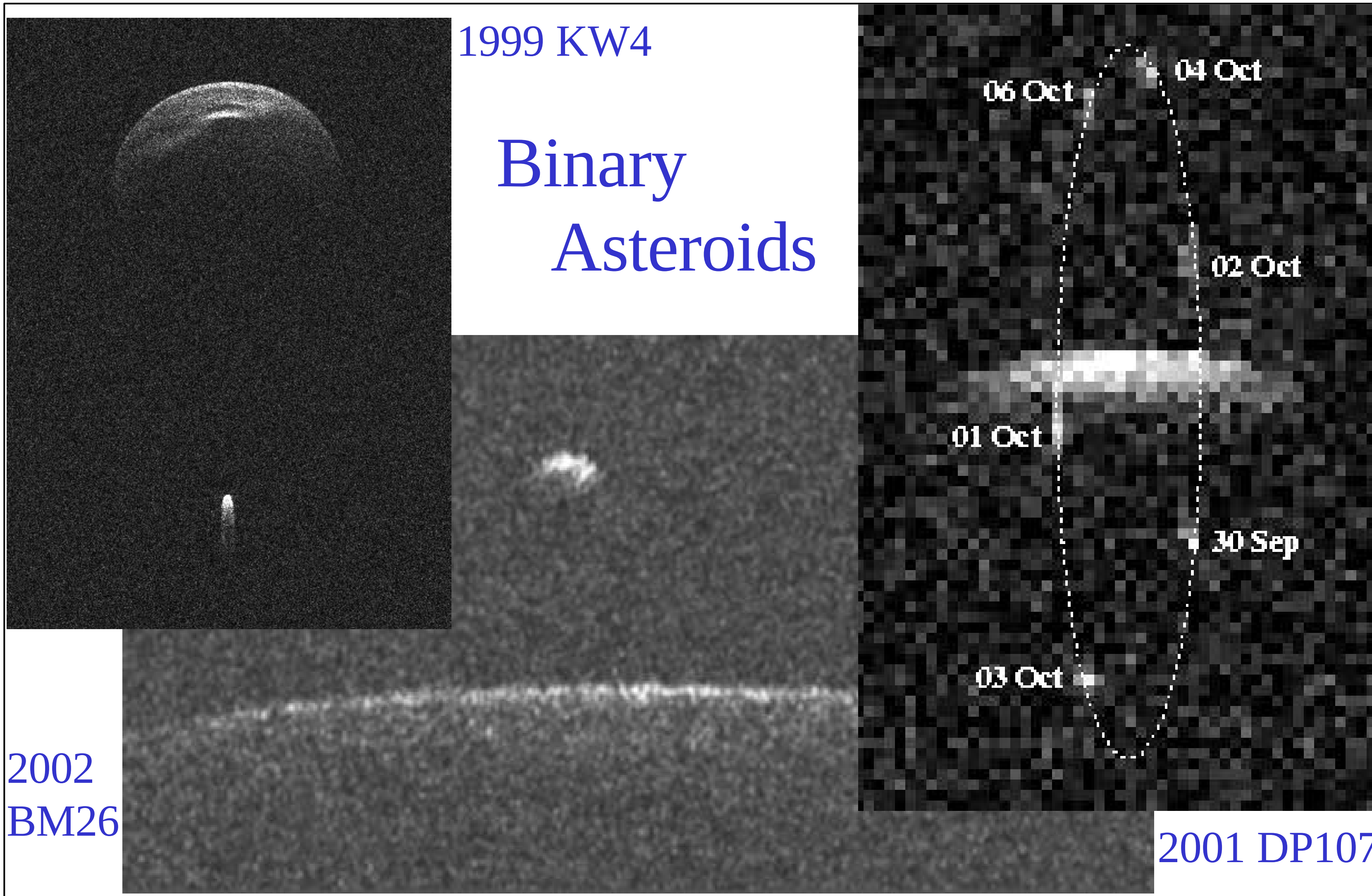
216 Kleopatra: Upper row – Arecibo delay-Doppler images; lower row – shape model showing aspect during data acquisition; middle row – model delay-Doppler images based on the shape model (Ostro et al).

Shape models for five NEAs and one mainbelt asteroid from Arecibo and Goldstone delay-Doppler images (R.S. Hudson et al)



NATIONAL ASTRONOMY AND IONOSPHERE CENTER

Binary Asteroids

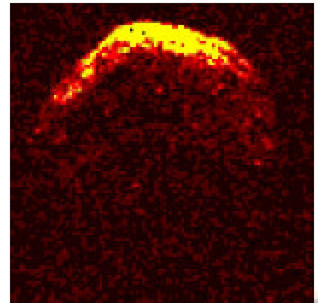


REPORTS

Asteroid 1950 DA's Encounter with Earth in 2880: Physical Limits of Collision Probability Prediction

J. D. Giorgini,[1] * S. J. Ostro,[1] L. A. M. Benner,[1] P. W. Chodas,[1] S. R. Chesley,[1] R. S. Hudson,[2] M. C. Nolan,[3] A. R. Klemola,[4] E. M. Standish,[1] R. F. Jurgens,[1] R. Rose,[1] A. B. Chamberlin,[1] D. K. Yeomans,[1] J.-L. Margot[5]

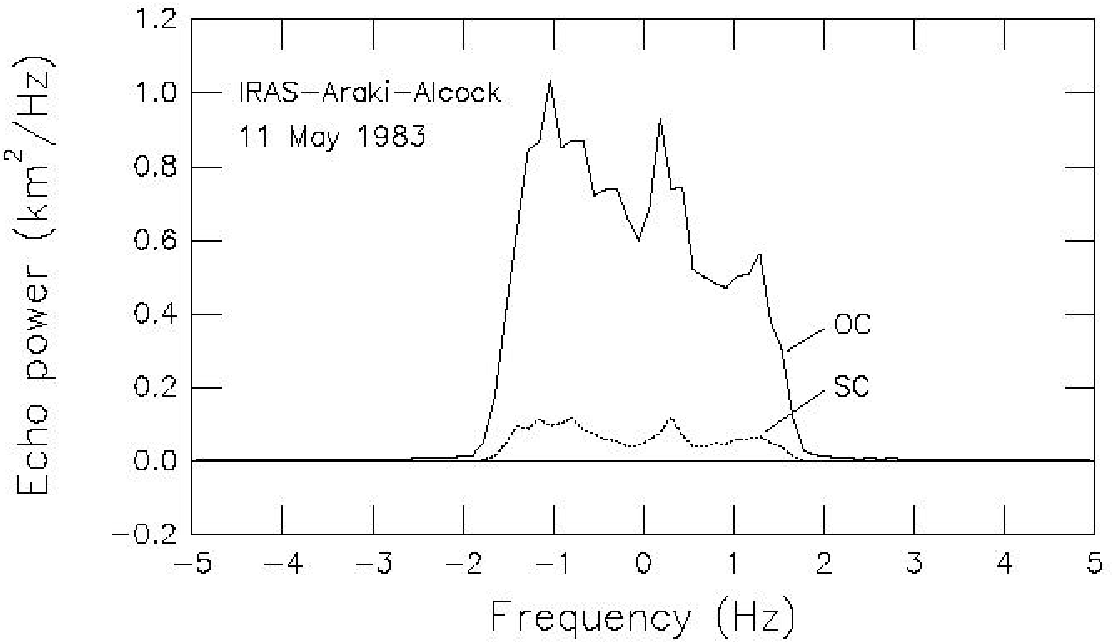
Integration of the orbit of asteroid (29075) 1950 DA, which is based on radar and optical measurements spanning 51 years, reveals a 20-minute interval in March 2880 when there could be a nonnegligible probability of the 1-kilometer object colliding with Earth. Trajectory knowledge remains accurate until then because of extensive astrometric data, an inclined orbit geometry that reduces in-plane perturbations, and an orbit uncertainty space modulated by gravitational resonance. The approach distance uncertainty in 2880 is determined primarily by uncertainty in the accelerations arising from thermal re-radiation of solar energy absorbed by the asteroid. Those accelerations depend on the spin axis, composition, and surface properties of the asteroid, so that refining the collision probability may require direct inspection by a spacecraft.



1950 DA

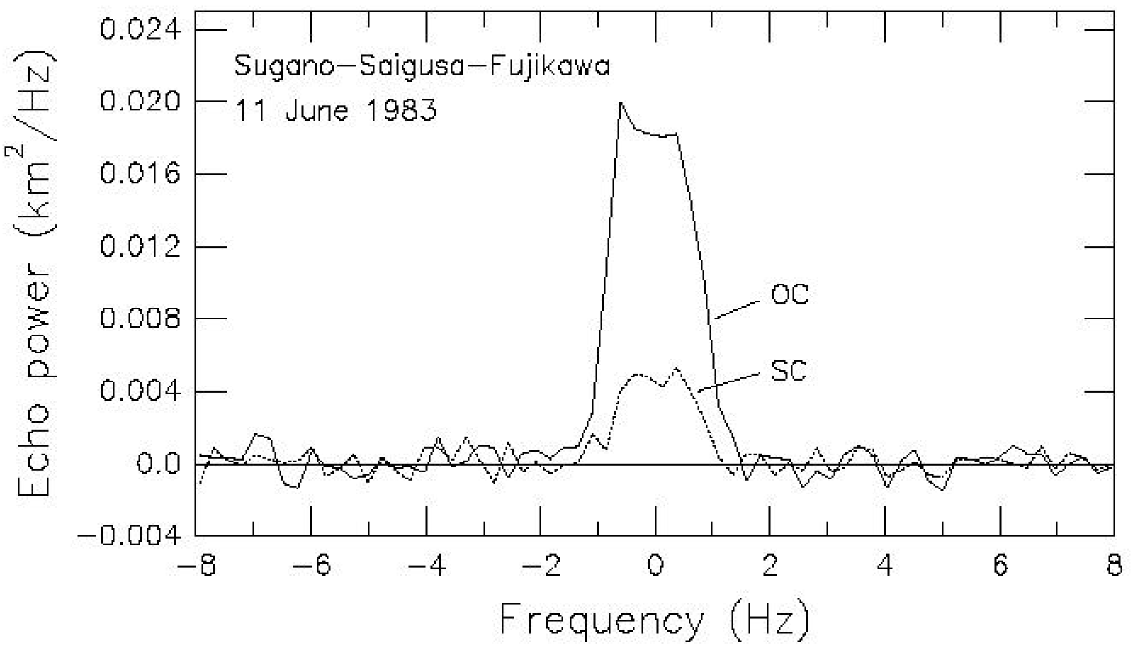
Arecibo radar image

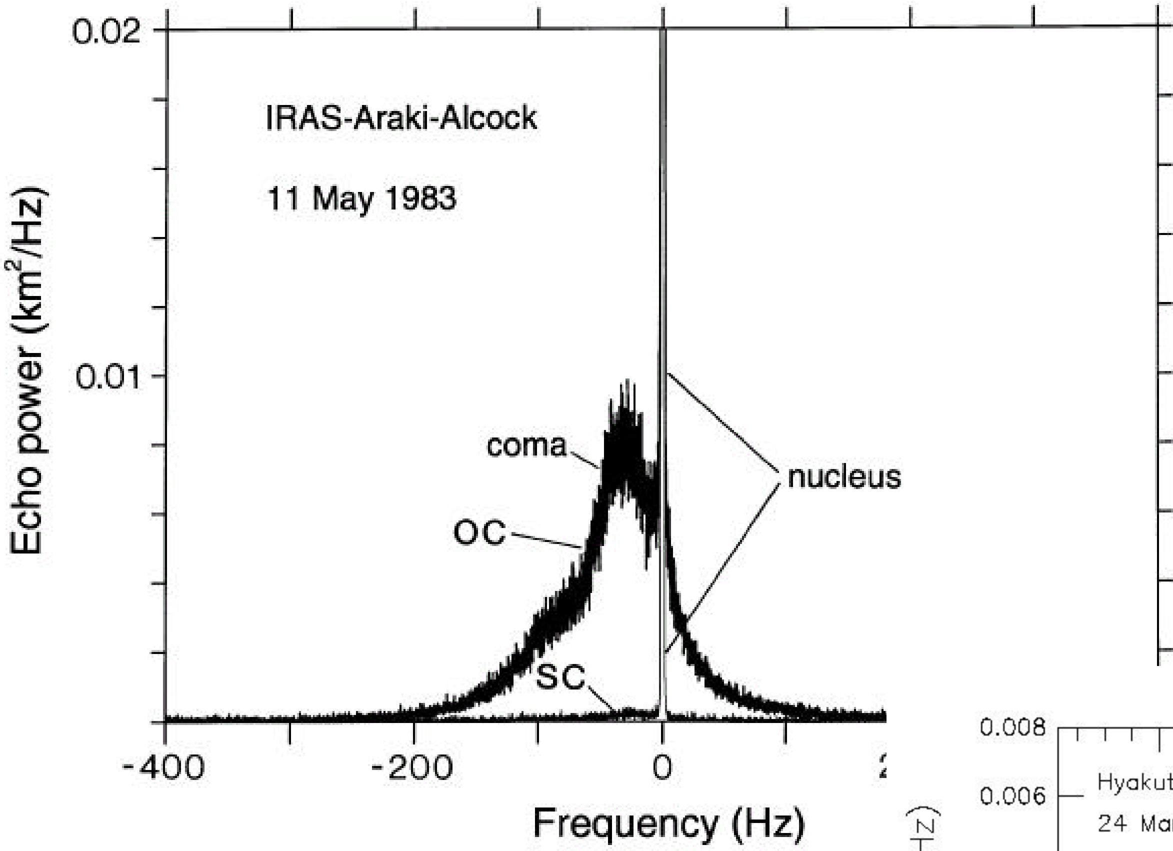
Comet Borelly from Deep Space 1 spacecraft



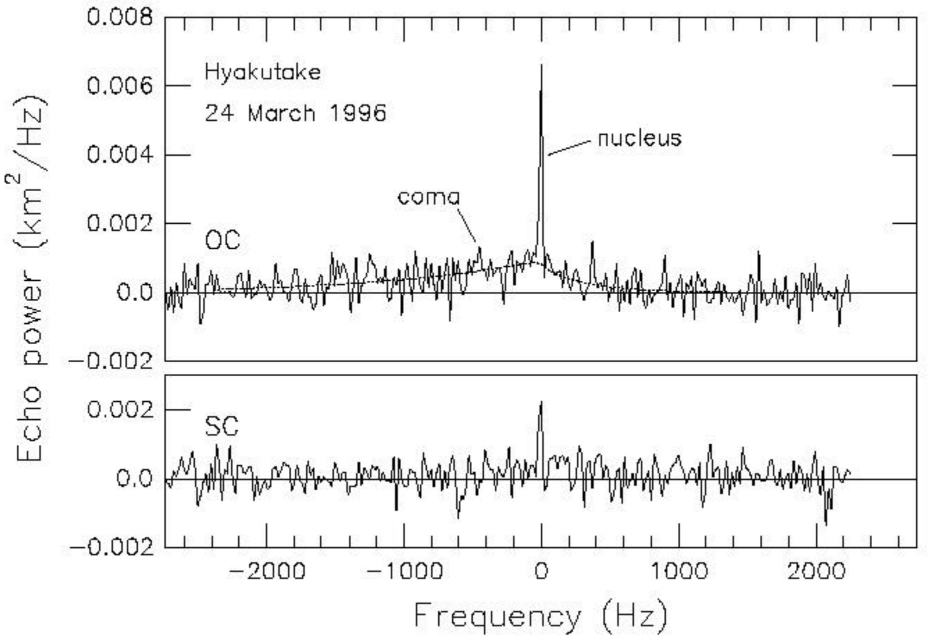
IRAS-Araki-Alcock
nucleus echo

Sugano-Saigusa-Fujikawa
nucleus echo





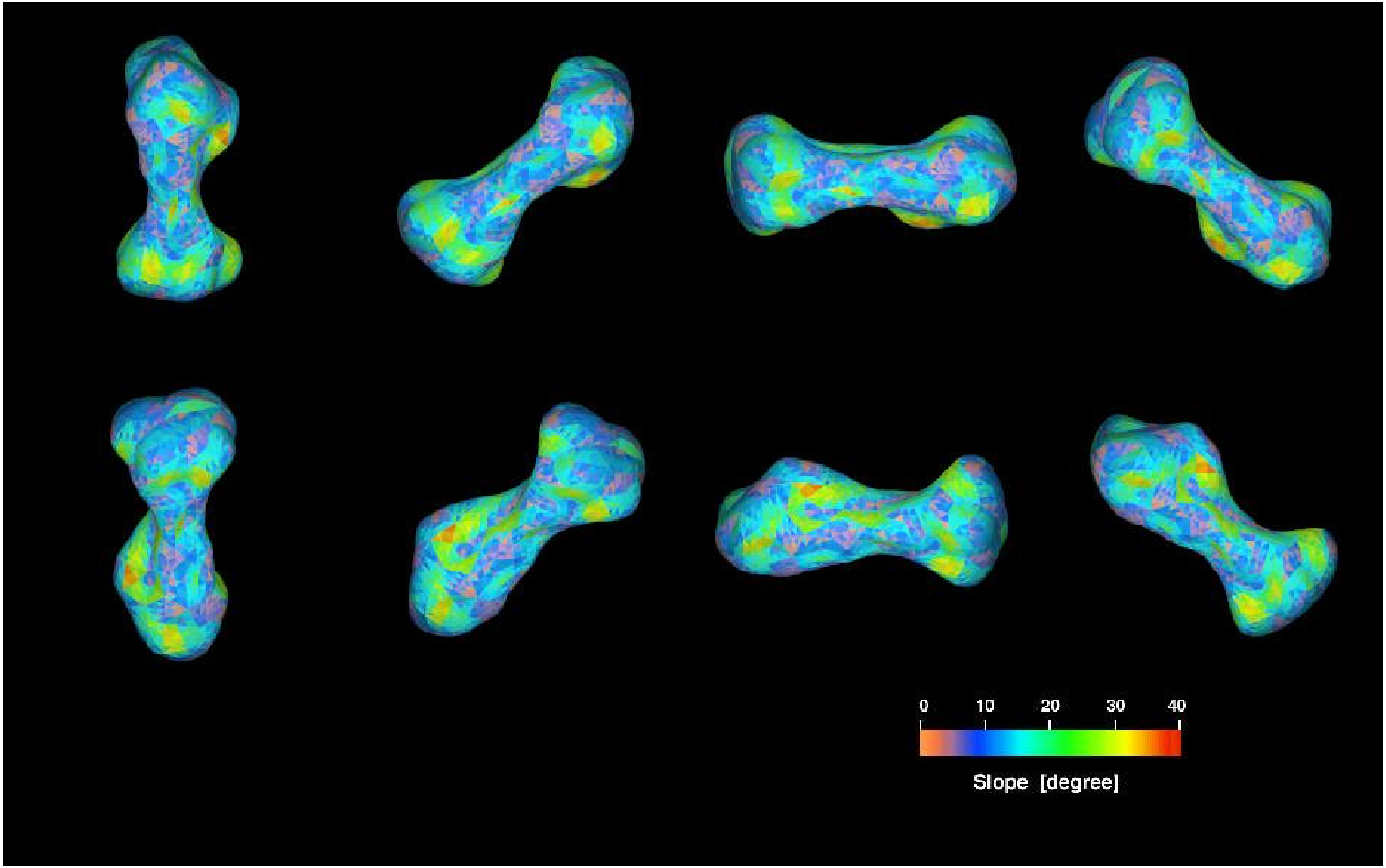
IRAS-Araki-Alcock Echo Spectrum

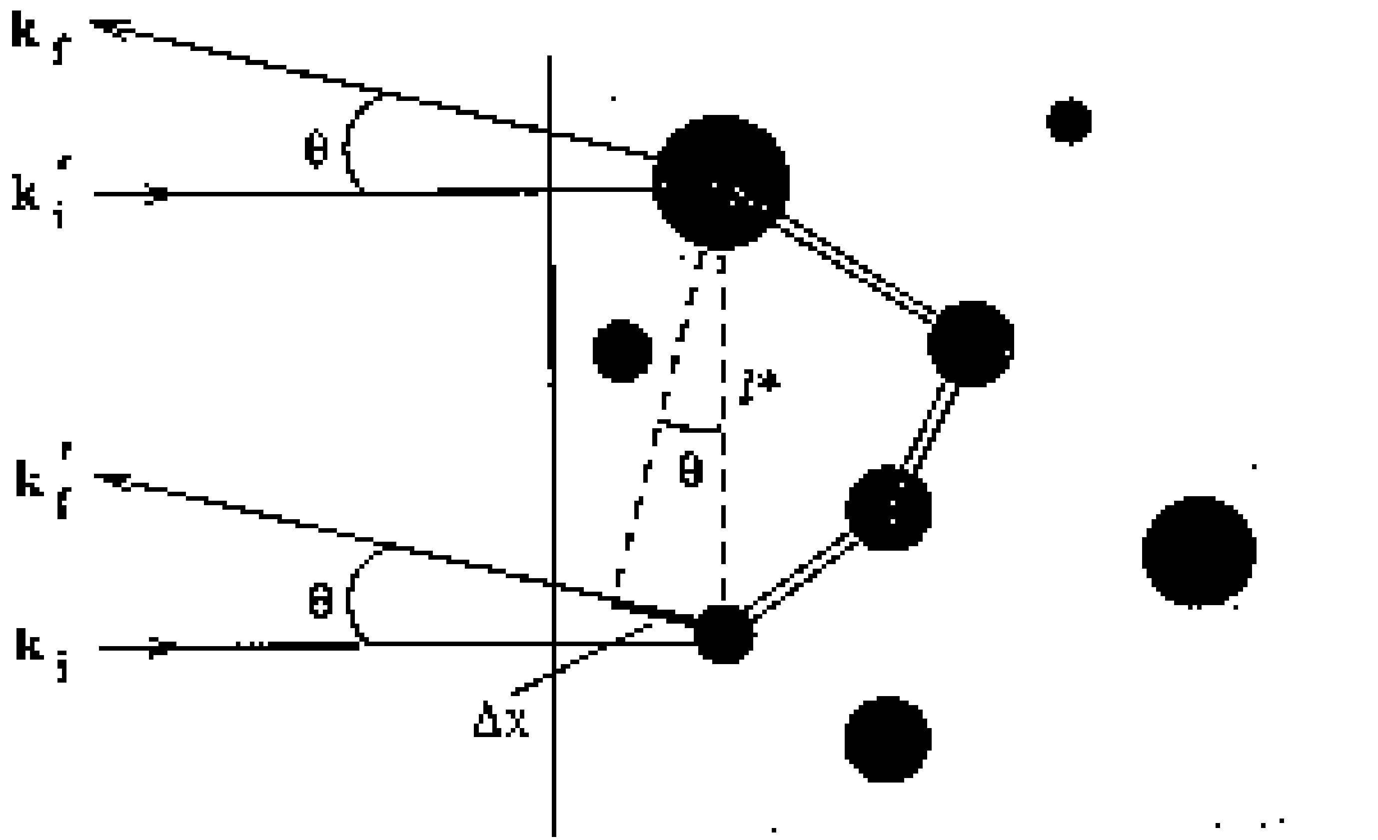


Hyakutake Echo Spectrum

PLANETARY RADAR ASTRONOMY

MODEL OF 216 KLEOPATRA
FROM ARECIBO RADAR DELAY-DOPPLER IMAGES
COLOR CODED FOR GRAVITATIONAL SLOPES





k f
θ
k'i
k'f
l*
θ
θ
k i
Δx