Radar Reconnaissance of Small Bodies and Icy Surfaces in the Solar System

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Landing spacecraft have directly characterized the surfaces of only the Moon, Mars, and Venus, but remote sensing, primarily with groundbased telescopes, has revealed salient structural properties of the surfaces of more than one hundred other solar system objects. Radar has been an extremely productive technique for investigating asteroids, which generally are too small and too distant to be resolved in detail by optical telescopes. The long wavelengths (3.5, 13, 70 cm) used at Arecibo and Goldstone during the past two decades in dual-circular-polarization observations have defined the degree of structural complexity on or near the surfaces of each of the radar detected bodies. Some main-belt asteroids have polarization signatures that require smooth surfaces at cm-to-m scales, whereas the angular scattering laws indicate rms slopes of a few tens of degrees at much larger, "topographic" scales. Some small asteroids return echoes with as much power in the same circular polarization as transmitted (the SC sense) as in the opposite (OC) sense; they must arise from some combination of single scattering from rough surfaces and multiple scattering.

SC/OC ratios higher than unity are seen in echoes from the icy Galilean satellites (Europa, Ganymede, and Callisto) and from polar anomalies on Mercury and Mars, in every case associated with unusually high radar albedos. The high radio-wavelength transparency of ice plus the structural heterogeneity of surfaces exposed over geologic time scales to meteoroid bombardment bound interpretations of the radar scattering processes involved. It is clear that some icy bodies do not return anomalous echoes -- all radar detected comets have low albedos and SC/OC ratios near zero. Conversely, some regions on Venus have SC/OC > 1 and high albedos. Therefore inferences about the presence or absence of ice cannot be based just on radar signatures. Moreover, various subsurface structures can produce identical radar signatures (Greenland's percolation zone returns echoes like those from the Galilean satellites, due to ice pipes that develop from annual cycles of melting and freezing).

Radar investigations of asteroids have proved invaluable in defining these objects' shapes and spin states. The observations typically use binary-phase-coded cw waveforms, usually with periodic codes but occasionally (and always for overspread targets, which are common in the main belt), coded-long-pulse waveforms. Single delay-Doppler images are potentially north-south ambiguous; the mapping from surface coordinates to the image can be many-to-one. If the radar view is equatorial, that ambiguity cannot be broken, but thorough rotation phase coverage uniquely defines the target's pole-on silhouette. If the orientational coverage includes enough views at least tens of degrees from the equator, then least-squares inversion of the images can yield a unique solution for the object's shape, spin state (eight free parameters), radar scattering properties, and refined estimates of orbit elements. Such global physical characterizations of several asteroids have revealed extraordinary diversity.