uncertainty introduced by the combination of this effect and the uncertainty in the earth-sun distances is much less than 0.1 percent.

The ACR402A sustained a precision of at least 0.1 percent during the period from May 1976 to December 1978, as is demonstrated by the two intercomparison experiments. No evidence indicates instrument performance outside this limit of precision in the two flight experiments conducted on 29 June 1976 and 16 November 1979.

We conclude that a high probability exists that the 0.4 percent change in solar luminosity observed between the two flights is real. Whether this represents a random fluctuation about a constant mean, an isolated change of short duration, or a sustained change that has climatological significance cannot be determined from these results. Additional rocket flight experiments are planned to help resolve this question, but solar monitoring involving the use of free-flying satellites and the space shuttle will be required to assemble an unambiguous long-term data base on solar luminosity. The principal contribution of continuous monitoring will be to establish its secular nature on time scales up to that of the persistence of photospheric faculae (~ 100 days), encompassing a range of solar phenomena with possible links to total luminosity that could lead to an improved understanding of solar physics.

In the future, the space shuttle may provide the optimum basis for compiling a long-term data base on solar flux with the accuracy and precision required to detect subtle trends in solar luminosity, trends that may have climatological significance. The shuttle will provide (i) the opportunity to compare flight and reference instrumentation before and after each mission, (ii) sufficient payload resources available for optimization of flight instrumentation, (iii) adequate flight duration for acquisition of solar data, and (iv) total flight exposure time too short to cause significant degradation of sensors by the environment of space. In addition to providing the climatology data base, the shuttle experiments can calibrate free-flying solar monitors, maximizing the accuracy and usefulness of their results.

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## Ganymede: Radar Surface Characteristics

Abstract. *Radar observations of Ganymede, at X-band, show that the surface is unusually bright and has unusual polarization properties. A model of the surface based on large numbers of random ice facets (hence vacuum-ice interfaces) is able to account for these characteristics.*

We report here the results of radar observations of Ganymede, Jupiter's largest satellite, at a wavelength of 3.5 cm. Measurements were obtained on six nights in December 1977, using the NASA spacecraft tracking facilities at Goldstone, California.

On each of the nights, we transmitted very narrow beams (0.04°) of monochromatic X-band radiation toward Ganymede for 1 hour and 9 minutes, the round-trip time of flight. During the ensuing 1 hour and 9 minute receive times, the frequency spectrum of the echo was measured continuously, using digital hardware. Altogether, 12 such send-receive cycles were completed, producing more than $2 \times 10^8$ individual spectra.

All of the transmissions were right-hand circularly polarized. Reflection from a smooth dielectric sphere completely reverses the sense of circular polarization. Thus, the radar echo would be left-hand circularly polarized were Ganymede a smooth reflector. Echo power in the original, right-hand, polarization sense is normally interpreted as containing information about the roughness of the object. To measure this effect, the receiver was configured to receive right-hand circular polarization on six of the receive intervals and left-hand circular polarization on the other six intervals.

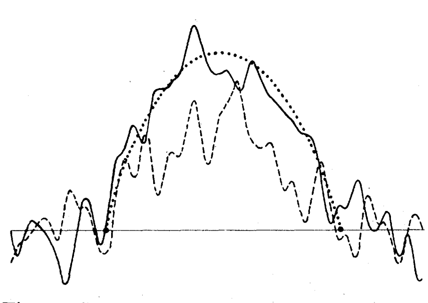

Fig. 1. Spectrograms of Ganymede echoes. Power density is plotted against frequency. (Solid curve) Power in the unexpected polarization, (dashed curve) power in the expected polarization, and (dotted curve) theoretical curve for a perfectly diffusing sphere.

During these measurements transmitter power averaged 343 kW, antenna (64 m) efficiency averaged 44 percent, and system noise temperature averaged 23 K. Although the system noise was extremely low, the power density of the Ganymede echo was always less than 0.007 of the noise power density.

Separation of the weak echoes from the very much stronger background was facilitated by a frequency hopping technique. Every 30 seconds the transmitter frequency was switched, alternately, between two values. On reception, the signal spectra were accumulated in two bins, each corresponding to a transmitted frequency. In this way, one of the resulting spectra served as a very stable baseline for the other.

In order to be sure of correct antenna pointing with such weak signals, we interrupted the observations between each change of configuration between transmitter and receiver and swung the antenna to nearby Jupiter. Jupiter, at a known small angular displacement from Ganymede, provided a very convenient microwave source for this purpose.

The resulting spectrograms, averaged over all of the observations for each of the polarizations, are given in Fig. 1. The full bandwidth processed was 5376 Hz. Dots, spaced 3037 Hz apart, mark the calculated edges of the Ganymede echo spectra. This bandwidth represents the maximum spread of Doppler shifts resulting from the known radius and rotation period of Ganymede. A theoretical curve, included in Fig. 1, gives the spectral shape to be expected if the surface of


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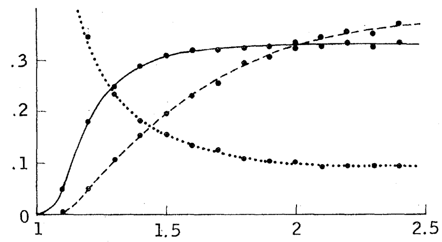


Fig. 2. Results of the computer simulation. Fraction of power backscattered is plotted against index of refraction of hypothetical ice surface. (Solid curve) Unexpected polarization, (dashed curve) expected polarization, and (dotted curve) their ratio (times 0.1).

Ganymede were a perfectly diffusing screen. It has the form $P(f) = 1 - f^2/f_0^2$, where $P$ is power density, $f$ is frequency, and $f_0$ is the rotational Doppler shift at the limb.

From the spectral data, we extract three attributes of the surface of Ganymede: the radar cross section in the expected polarization, the radar cross section in the unexpected polarization, and the lack of limb darkening as compared to a perfectly diffusing screen.

Table 1 gives these values, along with those of other reflecting objects of interest. The tolerance indicated for the Ganymede measurements is based on the scatter of the results for the different runs. Errors in antenna gain, system temperature, and so on have not been included. The surprising result that the unexpected polarization is strongest has been previously observed with 12.6-cm radar by Campbell *et al.* (*1*).

It is widely held that the surface of Ganymede is mostly ice. This view is justified by its low density, about 2 g/cm$^3$ as determined by mass (*2*) and radius (*3*) measurements. In addition, the signature of water ice has been found in infrared spectra (*4*).

A smooth sphere of ice, however, does not account for any of the radar characteristics of Ganymede, as can be seen in Table 1. Ostro and Pettengill (*5*) explained the 12.6-cm results by postulating large hemispheric craters saturating the surface of Ganymede.

We propose here a different model. It is based on the assumption that the upper few meters of the surface of Ganymede is ice, crazed and fissured and covered by jagged ice boulders. The index of refraction of the postulated ice is a free parameter of the model, as is the thickness of the cracked and faceted layer. The essential part of the model is a large number of ice-vacuum interfaces. Such a surface, by virtue of multiple reflections from random facets, would approximate a diffuse reflector and thereby meet part of the requirements of our observations.

An ordinary reflection from the vacuum side of an ice facet would reverse the polarization sense as long as the angle of incidence was less than the Brewster angle (54°). For greater angles, most of the power remains in the original sense. Neither reflection is particularly likely, since ice has low reflectivity.

Reflections from the ice side of a facet, however, are significantly different. The Brewster angle is only 36°, and beyond 46° the reflection is total. Thus the polarization sense is largely preserved and the reflected power is much greater, as required by the measurements.

We have written a Monte Carlo-type computer program to test these possibilities. In this program circularly polarized photons are numerically injected into a slab, modeling the surface, one at a time. A random facet (for which all directions are equally likely) is erected in the path, providing a vacuum-ice interface. The incoming photon is resolved into parallel and perpendicular (with respect to the plane of incidence) components. A random choice is made, based on reflected versus incident power, as to whether reflection or transmission occurs. The photon is advanced in the new direction one random step, the length of which is uniformly distributed between zero and two units.

This process is continued until the photon either traverses the slab and is lost on the other side or emerges from the front of the slab. In the second case, the polarization components and the direction of travel are recorded.

We found that the model simulates very well the behavior of a diffusing screen. The directionality of the emergent photons, the growth of backscattering with respect to slab thickness, and the growth of average number of facets encountered with respect to thickness, all are close to the values we computed analytically for an ideal diffusing (Lambert) screen.

The polarization results are given in Fig. 2, where the fraction of emergent photons in each polarization is plotted against index of refraction of the ice. The ratio for the two polarizations is also plotted. Noise, evident in Fig. 2, is the result of having a finite number of photons (3000) per test in the Monte Carlo program.

We find that for all indexes of refraction less than 2, the unexpected polarization is indeed stronger. Best fit to the Ganymede surface occurs at index of refraction equal to 1.4 and a slab depth of six mean free paths. Polarization ratios given by the model are essentially independent of slab depth to at least ten distance units.

Table 1. Radar cross sections ($\sigma$).

| Object | $\sigma$,* expected polarization | $\sigma$,* unexpected polarization | Limb darkening |
|---|---|---|---|
| Ganymede | 0.40 ± 0.06 | 0.81 ± 0.04 | None |
| Venus | 0.13 | 0.06 | High |
| Mercury | 0.06 | 0.005 | Moderate |
| Rings of Saturn | 0.7 | 0.7 | |
| Silver sphere | 1 | 0 | $\infty$ |
| Ice sphere | 0.08 | 0 | $\infty$ |
| Diffuse sphere | 4/3 | 4/3 | None |

*$\sigma$ is given in units of $\pi r^2$, where $r$ is radius.

For the best-fit condition, the average photon encountered 15 facets. Only 6 percent of these encounters were reflections from the vacuum side of an interface, whereas 57 percent were reflections from the ice side. Of the ice-side reflections, 97 percent were total. This explains why the polarization was largely preserved through the moderate number of random facets.

We conclude that our simplistic model of random facets easily accounts for both the unusual polarization and unusual brightness properties of the surface of Ganymede. The assumption was made that the facets are large compared to the wavelength, and the geometrical optics approximation was used throughout.

Of course, other scattering mechanisms must be operating. Reflections from edges and irregularities are expected to be about equal in the two polarizations. If these are significant, the index of refraction of the model must be reduced somewhat to restore the polarization ratio. Also, if the interstices between the vacuum-ice interfaces are filled with particles smaller than the wavelength, then the effective index of the ice must be less.

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