Anomalous region on Mars: implications for near-surface liquid water

S. H. Zisk
NEROC Haystack Observatory, Westford, Massachusetts 01886

P. J. Mouginis-Mark
Department of Geological Sciences, Brown University, Providence, Rhode Island 02912

An anomalous region has been identified on Mars from the 1971 and 1973 Earth-based Goldstone radar data. This region is characterized by coincident very high radar reflectivities, and unusual smoothness. Very few realistic surface morphologies can generate such return-signals. Liquid water within 50-100 cm of the surface is one possibility, an interpretation strengthened by an apparent seasonal variation in surface reflectivity for the same locality.

ANALYSIS of radar measurements of the martian surface enables textural-compositional differences of materials to be interpreted on a scale unobtainable from orbital images. Estimates of the dielectric constant (from inherent reflectivity) and small-scale slope statistics (see, for example, the C-factor analysis developed by Hagfors) can be used to characterize surface units or to delineate areas with unusual material properties.

An extensive data base was compiled from Earth-based radar measurements of the martian surface by Downs et al. in 1971 and 1973 at the Jet Propulsion Laboratory’s Goldstone Facility. This combined set of observations gave almost complete coverage between 14 and 22°S. The high dielectric constant of liquid water compared with both ice and dry geological materials means that radar observations should provide excellent evidence for or against the existence of water on Mars. In particular, this radar data set can provide additional evidence regarding the existence of near-equatorial regions of H2O outgassing (‘oases’) proposed by Huguenin et al. Liquid water should affect the radar characteristics of the surface, if any overburden is relatively transparent to the radar energy. If the water were allowed to form a free surface, as opposed to an adsorbed layer on a mineral substrate, then the radar-reflecting facets would be expected to be nearly horizontal due to gravitational forces. Hence this type of surface would give a radar return with a very high smoothness as well as high reflectivity. We report here our attempts to search for anomalous areas within the radar data set, where both high reflectivity and C-factor values could be attributed to a layer of liquid water or damp soil.

Experimental method

The radar determination of surface smoothness and reflectivity is derived from the observed variation of echo strength as a function of local incidence angle. The radar echo at any incidence angle is the incoherent sum of reflections from surface facets within the resolution cell which are oriented perpendicular to the radar beam. Strictly speaking, the reflecting surfaces are the Fresnel zones of these elements, so that the cross-section of each surface element depends on its radius of curvature or, where the radius is large, on its area. The size of the radar resolution cell is much larger than even the planetary-radius Fresnel zone. It is fixed by the resolution of the radar signal in time-delay and Doppler frequency, which respectively determine the resolution along the projected axis of rotation and at right angles to it. For the radar data considered here, the resolution cell measures ~80 km by 10 km, compared with the 0.9-km size of the Fresnel zone for the planet’s radius of curvature.

The C-factor parameter used to describe the surface smoothness quantitatively was derived by Hagfors. He postulated a set of models for surface topography (based on observations of the Moon), for each of which he calculated the number distribution of surface-facet slopes, and thence the expected curve of radar strength compared with incidence angle (C-factor template). The radar-observed curve was computer-fitted to these hypothetical curves to determine the best-fit value for the C-factor. For areas with moderate to high smoothness (C-factor > 100), the expression for the r.m.s. surface slope $a_{rms}$ is

$$a_{rms} = C^{-1/2} \text{rad}$$

For real surfaces which do not match these models, the measured curve of echo strength compared with the incidence angle will not agree well with any of the templates, and a large standard error will result from the fitting process. Smooth, random surfaces will generally show a good fit to the templates, because there is little dependence on the details of the model. Surfaces with high relief, on the other hand, cannot usually be described well by only one parameter. Also, a non-random surface such as an area of sand-dunes or a cluster of comparable-size craters, cannot be described well by the standard C-factor parameter at any observable amplitude of relief.

The morphology of the surface determines the shape of the curve and hence the value of C-factor. The amplitude of the curve is a function only of the reflectivity of the material of which the surface is composed, and is another independent output from the template-fitting process.

In the present radar measurements, the same surface-resolution element was observed at various incidence angles (by using the Doppler resolution in longitude) to form the curve of echo strength versus incidence angle. There is therefore no implicit
assumption of large-area uniformity of the surface, as was the case for some earlier measurements. Any systematic variation in surface composition as, for example, a low-reflectivity mantled surface interspersed with high-reflective, high-reflectivity rock formations, will show up as a poor fit (high standard error) to the C-factor templates. A mixture of high- and low-reflectivity materials exhibiting the same morphology will yield a low-error C-factor value, with an intermediate reflectivity. Other surface configurations can be hypothesized and their radar-measured parameters calculated. The reverse calculation, however, from the radar data to the surface configuration, cannot be carried out unambiguously for all combinations of reflectivity and C-factor. As the surface becomes less smooth, the variety of possible configurations increases and the reliability of the template-fitting becomes much worse, partly because of the reduced strength of the widely scattered signal and partly because of the above-mentioned variety of possible surface topographies.

Analysis
The data were scanned for regions with a coincident high reflectivity and smoothness. Limits of 9% reflectivity and 3,200 C-factor (r.m.s. slopes < 1°) were chosen arbitrarily. Variations from 9 to 11% and from 2,400 to 3,200 respectively had only a slight effect on the shape of the anomalous area and on the number of observation points. For these measurement values, the formal errors (standard deviations) were ~10% of the data value.

Figure 1a illustrates the arcocentric position and number densities of these high-reflectivity, high-smoothness measurements. Only two regions on the planet share this combined radar characteristic. The most prominent is a region centred at 16° S 90° W. There is also a pair of smaller areas to the north-west of Hellas. These two regions are remarkably close to the Solis Lacus (25°S, 85° W) and Noachis-Hellespontus (20° S, 310° W) oases proposed by Huguenin et al.

For comparison, Fig. 1b,c indicates the areas having only their reflectivity or C-factor above the defined limits. Note that there are many areas of high reflectivity, indicating a profusion of well-compacted or rocky soils on the martian surface. Areas of high smoothness are less common, although they are not restricted to the anomalies described here.

As an argument for the reality of the anomalous areas, note that the map of Fig. 1a includes radar measurements from both the 1971 and 1973 conjunctions. Almost no anomalous data points occur elsewhere on the planet, despite the near-global coverage of the data set between 14 and 22° S. In the 300 x 300 km anomaly itself, on the other hand, there are several hundred points.

Seasonal variability
Additional characteristics of Solis Lacus can be determined by comparing radar data derived for nearby coincident ground tracks at different times of the martian year. Note that practical limitations of Earth-based radar systems dictate that radar observations of the sub-Earth region must be made near opposition, and hence near local martian summer. Winter measurements would be extremely difficult to make using Earth-based radar.

A combination of data from the 1971 and 1973 oppositions provides an example of overlapping radar swaths: latitudes 15.45° S, 15.43° S, and 15.81° S were sampled between 80 and 100° W during the seasonal range from early to middle local martian summer (Ls = 258°, 273° and 294° respectively). Note that, as Ls represents the longitude of the Sun as seen from Mars, the difference between Ls = 258° and 294° is roughly equivalent to the shift from early June to mid-July on Earth (Northern Hemisphere). Because of the nearly identical locations of these radar profiles (the north–south extent of the radar resolution cell is 1.5°, giving an overlap of at least 70% between swaths), the reflectivity curves for identical surfaces should be very similar.

However, Fig. 2 indicates that there is a discrepancy in the reflectivity between Ls = 258° and 273°. The 273° profile indicates an increase of 1.0–1.5% in the reflectivity compared to the same longitude at Ls = 258°, while the 294° profile shows a further enhancement of 2.5–3.5%. For large parts of the region between 82 and 100° W, there is a systematically higher reflectivity with advancing Ls, that is season. Such a
Fig. 3  The seasonal variations in radar reflectivity compared here for three regions of Mars. The horizontal axis is reflectivity and the vertical axis is the percentage of data points having less than the indicated reflectivity. a, Compares the strongly anomalous Solis Lacus area with the weakly anomalous Noachis-Hellespontus region. b, Compares Solis Lacus with an area in Aeolis, which is taken to be representative of Mars as a whole and shows no anomaly. Note that all three areas display an increase in percentage reflectivity with increasing martian season, but that Solis Lacus has a much more pronounced seasonal change, in addition to its higher absolute radar reflectivity.

Fig. 4  Viking Orbiter Images of the anomalous radar areas. a, Ground track shown in Fig. 2; b, high resolution for an area in Solis Lacus at 18.7° S. Note that the images do not support a hypothetical smooth, mantle-free surface as an explanation of the radar anomaly. Numerous 10-km craters and lava flow fronts are in evidence (USGS photomosaics 1-1183 and 1-1190; and Viking frame 773A10). Scale bar, 3 km.
Discussion

Measurements showing a high radar reflectivity (high dielectric constant) would be expected not only for water surfaces, but also for large areas of smooth rock within 1 m of the surface. In these conditions, anorthosite rock, with a dielectric constant \(K\) of about 5, would have a reflectivity of about 15% (basalt, with \(K = 9\), is >25%; water, with \(K = 81\), is >65%) if it covered the entire surface area of the radar cell \((750 \text{ km}^2)\). Figure 4 presents Viking Orbiter images of the same area as Fig. 2. Although some craters larger than ~10 km diameter are within the radar ground track, many moderately well preserved lava flow fronts can be easily identified. Morphologically comparable lava flows elsewhere on Mars either have radar reflectivities of 2~6% or C-factors <2,000 (refs 5, 9, 10). Unless the small-scale surface texture of the Solis Lacus region is unrelated to its large-scale appearance in Fig. 3, the hypothesis of an extensive rock pediment is untenable as an explanation for the high values of radar reflectivity and C-factor.

Moreover, to explain a seasonal variability in the reflectivity of a solid rock surface, one must hypothesize, for example, an absorptive overburden which is regularly scoured away as the summer progresses. The thickness of overburden required for the observed changes in dielectric constant have been calculated on the basis of published dielectric constants and absorption lengths for basaltic rock and loosely-compacted rock powders. Although resonant effects of thin highly-planar soil and rock layers might be observed in laboratory conditions, such conditions do not exist on a planetary scale. Consequently, the reflectivity was calculated for a random-thickness soil layer masking a solid rock surface. Assuming dielectric constants of 2.0 for soil and 8.0 for rock, the net reflection efficiency for bare rock is 23%; for a soil layer at least 14 cm (one wavelength) thick, is 11%; and drops to 6% for a soil depth of 1.4 m. For lunar rock chemistry rather than terrestrial rock chemistry, the 6% reflectivity would require more than 10 m of rock-free soil. The problem is complicated by other factors such as variation in soil porosity with depth, but the conclusion, nevertheless, is that for rock and soil surface to exhibit a measured reflectivity of more than 11%, the soil thickness must be in the range from 10 to 20 cm over the entire area; and that an additional deposit of the order of 1 m of soil would be required to further increase the dielectric constant to 8%. Although there is undoubtedly a seasonal redistribution of martian dust, photographs at the Viking Lander sites do not show the buildup of the tens of centimeters of dust that would be needed to effect a change from 11% to 8% in the average radar reflectivity. Alternative explanations, such as seasonal changes in the bulk chemistry of the near-surface rocks, seem also to be unlikely.

Conversely, a transition from frozen water (reflectivity >7%) to liquid water (reflectivity >64%) would produce just such a striking difference in the observed radar reflectivity. Considerable supporting evidence exists that permits the presence of liquid water on Mars to be hypothesized. The large martian channel systems are believed to be the products of large-scale release and surface flow of water from confined aquifers. Thermal and IR-spectral measurements of the North Polar cap indicate abundant water ice, while 1–3 wt% of adsorbed water was detected in samples taken by the Viking Landers. In addition, on a smaller scale, both spectrophotometer measurements made during the 1973 dust storm and measurements from the Viking water-vapour mapping experiment indicate that a considerable amount of \(H_2O\) outgassing occurs at present within Solis Lacus. Although the surface temperatures at the Viking Lander sites are only in the range 233–250 K (ref. 19), for an assumed analogy with terrestrial geology the water reservoir could be highly saline due to the salts leached from the surrounding rocks. For Mars, saline solutions have been shown to be stable in their liquid phase in current surface conditions at temperatures as low as 210 K (ref. 21).

We conclude, therefore, that only surface materials containing liquid water are consistent with: (1) the coincident very high radar reflectivities and C-factor values; (2) the photographically observed near-surface morphological and mineralogical features; and (3) the increase in reflectivity values from spring to summer. Some inferences can also be made about the regional extent of the near-surface expression of the liquid water at Solis Lacus. An extensive liquid water surface (such as a lake) would have a much higher reflectivity than the observed maximum value of about 16%. More likely is a reduction in the reflectivity by an overlying layer of soil, as outlined above for the rock–soil combination, or, alternatively (or additionally), the liquid water might be observable only through random patches of the surface because of variations in the thickness or density of the overburden. In the latter case, the observed reflectivity values would be from a mixture of high and low reflectivity surface elements. In this case, the C-factor measurements would depend mainly on the highly reflecting regions (the oases) rather than the dry intervening areas. In either case, we are convinced by the radar data that liquid water does indeed exist near the surface of Solis Lacus during Southern Hemisphere summer.

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