REPORT OF THE VIRTUAL INSTRUMENT SCIENCE DEFINITION TEAM ON:

Facility Orbital Radar Sounder Experiment for MRO 2005 (FORSE)

April 9, 2001

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1. Executive Summary

Conclusions

1. Summary statement. The Italian Space Agency (ASI) Shallow Subsurface Sounding Radar (SHARAD) 20 MHz center frequency, 10 MHz bandwidth orbital radar proposed for the Mars Reconnaissance Orbiter (MRO) can probably detect liquid water and ice to depths of about 100 meters in the Mars subsurface. Identification of a reflector as being related to either form of water will require supporting information, and will likely be possible only where the porosity and saturation are high.
2. Depth of investigation. Globally, depth of penetration could be as little as one meter in materials with high losses (wet clays or brines), or as deep as 5 km in homogeneous, low-loss polar ice. These estimates of depth performance are based upon consideration of the high-level SHARAD radar system parameters against a background of ground-penetrating radar experience in terrestrial permafrost, sand dunes, and ice sheets. Further, these estimates assume reasonable scattering and material property characteristics, and the absence of perched brines, hydrated clay/zeolite minerals or significant magnetic mineralogy. If any of these conditions were encountered, the depth of radar penetration would be more limited. A reliable signal from a feature at depth requires a well-differentiated reflector such as a classical water table, and that the upper aqueous surface, either water or ice, is reasonably flat with respect to the *in situ* radar wavelength (which is on the order of ten meters).
3. Detection of Water. We presume that the surface of Mars will not be uniformly amendable to using radar sounding in the search for water. We further presume that it will be possible to find conditions of favorable radar viewing geometry, interface scattering, surface and volume scattering, and material properties, which may allow us to see useful reflections of aqueous layers from orbit. When strong internal reflections do occur, they will be identifiable as aqueous only by contextual inferences drawn from the characteristic geological context of water habitats.
4. Other Science Value. Independent of any ability to directly detect water or ice, the SHARAD radar should make significant new scientific data available toward addressing critical scientific problems on Mars, including the existence and distribution of buried paleochannels, regolith layering, an improved understanding of the electromagnetic properties of the “stealth” region, further insights into the nature of patterned ground, and other morphologies suggestive of the presence of water at present or in the past. In addition, it should be possible to answer certain kinds of geologic questions, such as the character of the surface below the polar ice caps and the nature of some of the layered terrain.
5. Relation to MRO Science Objectives. In addition to its primary impact on the first of the Group 2 objectives from the 2005 SDT report (detect liquid and frozen water), this instrument will contribute in a very significant way to the second and third of the Group 1 objectives. Regarding the second objective, sites with aqueous or hydrothermal activity are almost always associated with near-surface geological effects which may be imaged by GPR. Regarding the third objective, characterizing the stratigraphy requires information from below the top layer.
6. Relation to MARSIS, Nozomi. Deferring the design of SHARAD until after the data from Mars Express and Nozomi have been interpreted would be an advantage, but we do not consider it necessary. It is not clear whether either of these precursor instruments will produce interpretable

subsurface data. However, they should both provide information about background radio frequency noise sources, the transparency and attenuation of the atmosphere and ionosphere, the reflectivity of the surface, and possibly about the properties of the subsurface. Due to the absence of any direct HF/VHF radar measurements on Mars, SHARAD needs to consider a design that would minimize its risk by an appropriate choice of frequency to address issues raised in Section 4 of this document.

Recommendations

This team has reached consensus on the following recommendations:

1. We recommend that a radar sounding instrument be included in the payload of the 2005 Orbiter.
2. We recommend that the science objectives currently proposed for this radar instrument be modified. The science objectives currently stated will be difficult or impossible to achieve. However, there are many good scientific reasons beyond those stated for including this instrument.
3. We cannot endorse the detailed technical specifications for any given radar instrument at this time. We have been provided only generalized information about the proposed Italian radar, so this instrument would certainly fall within the scope of the above statement. There are a number of technical parameters that need to be carefully chosen and optimized relative to the instrument's science objectives. We recommend that these issues be worked prior to the PDR, and we have made some suggestions in the content of this report regarding these issues. However, we see no reason that these modifications would cause the instrument to exceed its resource allocations.

It is important to for the purpose of this document to clarify use of the word "detect", which is fundamental to the questions under discussion. There is an implied standard of certainty associated with this term which may mean different things to different people. For the purpose of this report, we use the term "detect" as a representation of the preponderance of evidence, rather than absolute proof, for which "identify" is used. An analogy which is partially relevant is that this is the sort of standard used in the U.S. legal system to distinguish civil and criminal judgements.

2. Introduction

Assessment of Shallow Subsurface Sounding Radar Concept

TO: David Beaty
FROM: Richard Zurek
DATE: March 21, 2001
SUBJECT: Assessment of Shallow Subsurface Sounding Radar Concept

After weighing various factors, including the likely timing of MARSIS data acquisition and analysis and the present absence of data characterizing the Martian subsurface, the Mars Reconnaissance Orbiter (MRO) Science Definition Team (SDT) recommended that a subsurface profiling radar be flown sometime as part of the Mars Exploration Program (MEP) and that, for the 2005 launch opportunity, it be considered for flight through the AO process as a Group II Science objective. As a reminder, Group II objectives were regarded as having high scientific priority for MEP, but also entailed significant risk with regard to implementation as an optimal experiment for a mission launched in 2005. The SDT further recommended that any radar considered for flight on MRO should focus on the detection of liquid water and the profiling of water ice in the uppermost 1 km of the Martian surface.

Since the deliberations by the SDT in January, NASA has continued to study possibilities of enhancing future science return within the MEP. One activity well underway is the possible provision of a communications satellite for Mars to be built by the Italian Space Agency (ASI) and to be launched to support missions arriving at Mars after 2007. In return, NASA and ASI are considering flight of a shallow subsurface sounding radar (SHARAD) to be flown on the MRO. The ASI team has proposed a single frequency, 20 Mhz, radar system, which they believe will penetrate from 300 m to 1 km into the Martian subsurface.

As co-chair of the MRO Science Definition Team, I would like you to reconvene at least a subset of your radar study group to address the following issues:

1) Can a single frequency (20 MHz), wide bandwidth (10 MHz), credibly detect liquid water and characterize unambiguously the distribution of water ice in the uppermost part of the Martian subsurface (< 1 km)? Factors to be considered are:

- i) Will the system be able to detect water and water ice if present in the 0.3 - 1.0 km depth zone, as well as nearer the surface?
- ii) How definitive will the detection of liquid water be?
- iii) How definitive will the profile of subsurface ice distribution be?

2) Assuming that the single frequency approach is deemed credible, are the other basic design features proposed for SHARAD (mass, power, data rate, antenna length) appropriate to achieve the science objectives?

- Detection of liquid water to depths of 0.5 km or more
- Detection and profiling of water ice to depths of 0.5 km or more, with vertical resolutions of 10-30 m (emphasizing best resolution near the surface)

3) If there are uncertainties in the technical ability to achieve the science objectives, would these be substantively reduced if MARSIS data were in hand?

Let me thank you and your group in advance for assisting us in assessing the scientific
desirability of this potential MRO facility radar. Because time is short, I ask that you
provide us a report by April 9.

More information on requested RADAR analysis

TO: David Beaty
FROM: Jim Garvin
DATE: March 21, 2001
SUBJECT: More information on requested RADAR analysis

CONCEPT CHARTER "IDST" STUDY (a virtual IDST)

Given the WHITE PAPER of the Sub-Surface Working Group chaired by you and the science drivers framed in that Document, plus the science priorities discussed by the 2005 MRO SDT (cf. copy by Zurek and Greeley, 2001), what are REALISTIC measurement objectives for an orbiting sounding radar for the MRO, given mass, power, and observational constraints? What is a realistic top-level instrument design approach (frequency, bandwidth, etc).

CONSTRAINTS (boundary conditions):

Facility Orbital Radar Sounder Expt for MRO 2005 (FORSE):

MASS: 15 kg (with max of 3 kg contingency). Not to exceed 18kg (if it does it will be deleted)

POWER: Peak (during transmit) <+ about 60W with standby or OFF mode

EMI/RFI: TBD but depend on Jim Graf's spacecraft RFP specs

DATA: Observations to be made when the GROUP 1 High res. sensors are NOT collecting data (i.e., nightside), in targeted mode, avoiding data playback times (downlinks); data volume constrained (Rich Z. knows what is realistic here)

SCIENCE (to be traced by IDST STUDY TEAM as above): SHALLOW ONLY sounding, with focus on uppper 300-1000m, at highest possible along-track sampling (< 1 km) and with potential for 10m vertical resolution depending on dielectric contrasts and geoelectric properties. Aim is to explore layering structure of upper 100's m at high spatial and vertical resolution, provide complementary data to MARSIS, and set the stage for a dedicated orbital radar satellite perhaps in the 2009 opportunity (maybe a SAR/sounder?). This is to be an EXPERIMENT and not a mapping instrument and we need to know under what natural conditions a FORSE instrument might detect subsurface ice, water, clathrates, etc. definitively enough to warrant surface-based sensing or drilling (maybe in 2007).

Given these constraints and the further policy that the FORSE will not have any observational priority over the high res. or climatology sensors during the primary mission (one Mars year), what are the most desirable system parameters to optimize such a system? In other words we want the virtual IDST to address in a forward sense what might be the most risk-adverse approach for this EXPERIMENT (a shallow radar "pathfinder" rather than the definitive global mapper). For example, must we have a multi-frequency approach or interferometric observations or ...

Given that result, then does the tentative, proposed ASI "design" [20 MHz, 7 m tip to tip dipole, etc. etc.] meet the standards of the charter in terms of boundary conditions (constraints) and top level design choices.

Furthermore, does ANY single-frequency 20 MHz radar sounder address the SSWG/SDT (and MEPAG) top measurement objectives?

Clarifying note added based on discussion of March 30, 2001

- Given current mission priorities, we cannot expect that this instrument will be used for global mapping. With its relative priority, it is likely to used to investigate targeted areas. There is potential for the amount of coverage to go up substantially during the extended mission.
- Given that Mars is inhomogeneous, it is of questionable value to ask if a GPR will detect water on an average Mars. What would be of more would be to model the best and worst cases. Is there ANY combination of conditions on Mars that would allow useful data to be collected?

In response to the above two pieces of correspondence, an Ad Hoc Instrument Science Definition Team (see cover sheet for members) was formed on March 23, 2001. Results were requested by April 9, 2001, and if possible, by April 6, 2001. This team therefore conducted the following analysis over a period of about two weeks.

3. Detection of liquid water and water ice

1) Can a single frequency (20 MHz), wide bandwidth (10 MHz), credibly detect liquid water and characterize unambiguously the distribution of water ice in the uppermost part of the Martian subsurface (< 1 km)? Factors to be considered are:

i) Will the system be able to detect water and water ice if present in the 0.3 - 1.0 km depth zone, as well as nearer the surface?
ii) How definitive will the detection of liquid water be?
iii) How definitive will the profile of subsurface ice distribution be?

Summary

No, in general. The dielectric contrasts between dry rock and ice-rock or water-rock mixtures at moderately low porosity (<10%) are comparable to the contrasts that might be expected between different dry rock or soil types or due to stratigraphic variations in density, and so water or ice cannot always be confidently identified from reflectivity alone. Water in high-porosity (>20%) aquifers could be identified with relatively high confidence. As such high porosities are most likely in the shallow subsurface, high-level water is a good target for radar sounding. Massively segregated ice may also be detectable but, on the basis of reflectivity alone, could be confused with low-density regolith. In general, ice or water must be identified *qualitatively* from the geological context of subsurface reflections (see response to Question 4). This is best done with some ability for 3D geological mapping (not necessarily true 3D imaging) and will require areas 10s of km in diameter with orbit tracks spaced 100s of m to km with good orbital positioning and antenna orientation information. Layering, scattering, and absorption may limit the effective depth of exploration of 20-MHz radar to a fraction of the desired design depth, perhaps as low as 20–100 m.

Limitations imposed by the volume of ice or water

First, it must be recognized that radar cannot unambiguously identify water as, for example, a mineral is identified in a thermal or visible spectrum. Dielectric-relaxation responses can uniquely identify water and ice, but these lie at frequencies of >10 GHz and <10 kHz, respectively, well above and below the GPR radar band, and above 10 GHz the depth of investigation will be far less than one meter. The dielectric relaxation of clathrate hydrates (Davidson, 1973) at frequencies of a few MHz may be directly detectable by radar. In general, though, radar detection of water must then be based on a contrast in dielectric constant. At radar frequencies, representative dielectric constants for rock, liquid water, and ice are 6, 87 (near freezing), and 3, respectively (Fletcher, 1970; Hasted, 1972; Franks, 1972; Olhoeft, 1981), with stronger temperature dependence in ice than liquid water, and hardly any in rock. The large difference between rock and water appears to be very favorable for water detection, but not for water identification without measuring through the frequency of a water or ice dielectric relaxation. For groundwater in pores, however, the effective contrasts are much smaller. At 5% porosity, perhaps characteristic of solid rock at depths of kilometers, the dielectric constant of a rock-water mixture is 7-9, indistinguishable from modest contrasts between different rock (these calculations use the well-known Hashin-Shtrikman bounds, but even simple linear mixing by volume will illustrate the point; Shivola, 1999). As the dielectric constants of most kinds of rock can be expected to lie below 10 (but can be as high as 15 in some rock types), larger values derived from radar sounding would be strongly suggestive of water. The HS bounds would therefore require the porosity to exceed 10-30%. This is not unreasonable for poorly compacted regolith or porous sedimentary or volcanic rocks (in some basalts, porosities in excess of 90% are possible). As high porosity is more likely to be found closer to the surface, high-level groundwater is a good target for radar sounding. This conclusion is based on the expected reflectivity alone and does not consider scattering or absorption losses (see below).

Detection of ice is much more ambiguous, because the contrast is smaller: the dielectric constant of the rock-ice mixture will not decrease to 4 until ice fills 60% of the volume. Therefore only massively segregated ice such as ice wedges or pingos, and not ground ice filling normal porosity, is likely to be observable. However, reflectivity-based discrimination may still be difficult, because dry regolith or soil layers can have dielectric constants comparable to that of ice (~4 @ 2 g/cm^3) (Olhoeft and Strangway, 1975, Carrier et al., 1991).

Identification of water and ice on Mars based on radar reflectivity is then likely to be statistical, with higher confidence being assigned to larger apparent dielectric contrasts. At present, however, we do not know if the geologic conditions favoring direct detection are met, and therefore large amounts of groundwater exist that cannot be confidently identified. If the "preponderance of evidence" suggests the presence of water or ice, it will be acceptable to indicate such detection. Radar may never lead to confirmation of water or ice on Mars with "beyond a reasonable doubt" identification. The most likely scenario is one in which characteristic statistical heterogeneity patterns in geology (that are caused by processes involving water movement) will be detected in the subsurface geology if the radar system has sufficient resolving power: buried stream beds and channels, patterned ground from freeze-thaw and wet-dry cycles, ice wedges and pingos, etc. (Schaber et al., 1986, Olhoeft, 1994).

Depth of investigation

Major concerns exist about the ability of the radar to penetrate to the desired depth (300-1000 m). Penetration is controlled by a variety of signal losses, including geometric spreading, electrical conduction, dielectric and magnetic relaxations, and interface and volume scattering. These losses all cause frequency dependences which complicate signal processing, as can constructive and destructive interference from multipathing, waveguiding, etc. Frequency dependence especially complicates signal deconvolution. Waveguide effects are not expected to be a problem (though the properties of the Martian ground-ionosphere waveguide are unknown, they probably occur at significantly lower frequencies). Multipathing may be a problem when cross track reflections occur from severe topography (mountains like Olympus Mons and the deep canyons), and they will most impact the shallow subsurface interpretation much like the similar problems on the Apollo 17 orbital Lunar Sounder Experiment (ALSE, 1972; Phillips et al., 1973; Porcello et al., 1974).

As an example of one control on penetration, consider the total dB loss as a function of average dielectric contrast and thickness of rock layers. If layers average 30-m thick and have a 10% contrast, the two-way loss is 15 dB/km; such interface losses would likely be deemed acceptable. If, however, layers average 10-m thick and have a 20% contrast, then the two-way loss is 90 dB/km, which would likely limit penetration to a few hundred meters or less. Terrestrial experience using 80-MHz GPR in permafrost and sand dunes would suggest a reasonable expectation of less than 100 meters penetration (Olhoeft, 1975, 1977, 1980, 1994; Olhoeft et al., 1979; Schaber et al., 1986; Schenk et al., 1993), though more might be possible based upon recent experience in the dry valleys of Antarctica (S. Arcone, 2001, U.S.Army Cold Regions Research and Engineering Laboratory, personal communication).

More detailed models of the radar return also include effects of 3D propagation, pulse shape, antenna beamwidth, volume scattering, surface scattering, and absorption in addition to layer reflectivity. These simulations (in Appendix 1) demonstrate that water and ice can generate measurable reflections, especially when aided by SAR processing, from depths up to several hundred meters. Under more conservative assumptions, the depth of exploration may be limited to 100 m or so and, under unfavorable conditions, could be limited to ~20 m. In all cases, interpretation of the reflectors as ice or water is subject to the same uncertainties discussed above.

One aspect of the simulations that may require further exploration is volumetric scattering. The distribution of rocks was set to have a mean diameter of 1 m and a volume fraction of 5%. The Viking and Pathfinder sites have some rocks that are much larger than this, yet were considered relatively smooth to be chosen for landings. A power-law distribution of clast sizes is expected for megaregolith and therefore larger scatters, while less abundant, may certainly be present.

The magnetic properties, especially potential ferromagnetic and superparamagnetic relaxation losses, are of particular concern at both low (Olhoeft and Strangway, 1974) and high frequencies (Olhoeft, 1991, 1998). On Viking and Pathfinder, there were experiments to measure static ferromagnetic properties (Morris et al., 2001). These are important, but say nothing about dynamic magnetics in fine dusts, especially superparamagnetism, which is commonly observed in the fine volcanic dusts in Hawaii (J. Kauahikaua, 2001, USGS Hawaiian Volcano Observatory, personal communication). On the earth, the Swedish airborne CARABAS GPR had problems with thin layers of magnetite in the Yuma tests in the Lechiguela Desert in southern Arizona where the magnetic losses were significantly higher than the electrical losses at radar frequencies (Olhoeft and Capron, 1993). This is also true in Idaho, several places in Colorado, and Australia. Dry or freeze the water out of those systems and the magnetic loss dominance gets even larger (in the absence of clay and zeolite minerals).. Thin layers of magnetite at Great Sand Dunes National Monument also form strong reflectors (Schenk et al., 1993). However, in many "red" soils, especially in the Western US and Australia, the superparamagnetic component dominates, strongly influencing the frequency band from kilohertz to hundreds of megahertz (Taylor et al., 1987; Spies and Frischknecht, 1991; Hansen et al., 1996). We know nothing about this on Mars. The JSC-1 Mars soil simulant is not magnetic in the dynamic sense, but this is probably only because this property has not been measured in situ! The mineralogy may be subtly different (the static magnetics measurements on Pathfinder have not produced definitive mineralogy limits, Morris et al., 2001).

Furthermore, a little titanium with the iron oxide magnetic minerals can also have a large effect (Dunlop and Ozdemir, 1997). One important point is a little titanium can make the Curie temperature drop dramatically, so that the difference between day-night or winter-summer is a material that is ferromagnetic when cold, and paramagnetic or superparamagnetic when warm, even on the earth (but especially true in the wider temperature swings of the moon and Mars). That suggests it will be important to measure both day and night responses (complicated by the differences in the ionosphere between day and night on Mars).

Some specific comments regarding imaging of the "water table" and the 3D distribution of water

Thin films of liquid water exist on mineral surfaces at subfreezing temperatures because of the difference in molecular structure between the mineral and bulk pore water (Anderson and Tice, 1973). This unfrozen water is observed in fine-grained terrestrial soils down to temperatures of -140 C (McIntosh, 1966; Forslund and Jacobsson, 1975) and could exist at lower temperatures on Mars due to the freezing-point depression in saline groundwater (Brass, 1980). The unfrozen water tends to be interconnected and thus is electrically conductive to thicknesses approaching a monolayer. The attenuation of EM waves will be strongly dependent on the salinity of martian groundwater. If shallow groundwater is very fresh, then radar may penetrate through the unfrozen water in the cryosphere and directly detect a larger contrast with subcryospheric water. On the other hand, even moderate salinity may absorb all the energy: the presence of water would be inferred from the lack of a radar return and the depth to true groundwater below the cryosphere would have to be estimated from geothermal models. Similarly, it is very unlikely that radar will be able to penetrate substantial depths into martian groundwater in order to map its 3D distribution. Low-frequency EM methods, with greater skin depths, are necessary for this, at the expense of poorer vertical resolution.

Finally, the presence of capillary water in a subcryospheric vadose zone may not provide a distinct water table to be imaged from dielectric contrast. In fine grained soils with thick capillary fringes, airborne GPR, which is similar to an orbital radar, has not been very successful in identifying water tables on the Earth. We can find only a few cases where stronger radar returns were correlated with water tables in very dry areas with very little loss in such soils. However, GPR has been successful at identifying water tables below coarse-grained soils. In these cases, water presence must be inferred from the bulk dielectric constant of a layer using the apparent velocity of that layer.

Even with these constraints, it is possible that the depth to water can be approximately mapped in three dimensions. True 3D imaging would require that orbital tracks be spaced and precisely known at distances comparable to a wavelength (15 m), which is impractical. Instead, synthetic-aperture processing can produce useful 2D images along track, which can then be interpreted for 3D structure under the usual constraint that the geological structure itself does not vary in the cross-track direction much faster than the orbit spacing and assuming no problems from cross-track multipathing.

4. Will the design of SHARAD achieve its science objectives?

2) Assuming that the single frequency approach is deemed credible, are the other basic design features proposed for SHARAD (mass, power, data rate, antenna length) appropriate to achieve the science objectives?

- *Detection of liquid water to depths of 0.5 km or more*
- *Detection and profiling of water ice to depths of 0.5 km or more, with vertical resolutions of 10-30 m (emphasizing best resolution near the surface)*

Summary

The ability of SHARAD to achieve the science objectives will be largely dependent on the electrical properties, both permittivity and permeability, of the soil, degree of scattering off the surface and volumetric debris, and the stratigraphical layering of the subsurface. Due to a high level of uncertainty in the above parameters, it is possible, given the appropriate subsurface model, to predict both success and failure, with the median of partial success indicating ambiguous detection of some of the subsurface layers.

Although the level of uncertainty in the subsurface characteristics of Mars is high, the surface features such as surface roughness and slopes are better understood thanks to recent information from MGS (Mars Global Surveyor). These information can help us in designing a more optimum radar. As it will be described below, the **most important** design parameter is the choice of the operating **frequency**.

It is important to not overstate the capability of the proposed GPR to detect liquid water to depths of 0.5 km or more and to detect and profile water ice to depths 0.5 km or more with a vertical resolution of 10-30 m, as there is a very good chance it may not be able to even detect water or ice unambiguously.

It is important to note that the authors of this report, during its preparaton, had very little information regarding the technical specifications of the proposed SHARAD instrument.

Frequency Selection

The primary design features influencing the detection and vertical resolution capabilities of the radar are the operating frequency and bandwidth, in which there are obvious trade-offs. In order to meet the above stated objective of a vertical resolution on the order of 10-30 meters, a corresponding bandwidth of at least 2-6 MHz is required (assuming a dielectric constant of 2.5).

The science objectives for the MRO radar are different from those of MARSIS. The maximum required penetration depth is 1 km and there is a call from the science community for higher spatial resolution in both depth and lateral dimensions. Consequently, it may be possible (and necessary) to increase the radar operation frequency to accommodate the increased bandwidth. In this respect, the ASI proposed radar SHARAD presents an appropriate concept by operating at a higher frequency (e.g. 20 MHz). However, the increase in the operation frequency needs to be balanced considering the following factors (with the <u>increasing frequency</u>, the correlation is shown in () and the impact on the performance is shown in [ ]):

3 Depth of penetration (-) [bad]
4 Attenuation due to the volumetric scattering (+) [bad]
5 Surface clutter (volumetric debris) (+) [bad]
6 Sensitivity to surface height r.m.s (+) [bad]
7 Ionospheric dispersion and attenuation (-) [good]
8 Faraday rotation due to the Mars magnetic field (-) [good]
9 Spatial resolution (+) [good]

Depth of Penetration

Obviously, the decreased depth of penetration is the prime concern of all the factors listed above. It is essential for the system to achieve even the least acceptable penetration to produce any scientific return regardless of any other positive impacts. As stated in section 3, the penetration depth could vary from meters for the worst conditions to a few 10s of meters for the average conditions and up to hundreds of meters for favorable conditions. Under worst case conditions, the penetration depth will be on the same order as the resolution and it is likely the radar will be unable to detect anything; however, it is unlikely that this would represent the global conditions of the planet. For both average and favorable condition, the penetration depth should be sufficient enough to obtain responses off the subsurface layering.

Attenuation due to the volumetric scattering

Other than the decrease in penetration depth, increasing the operating frequency will increase the attenuation due to scattering of volumetric debris. At both the Viking and Pathfinder landing sites, a significant amount of surface rocks were observed. These rocks varied in size from a few cm's to as large as 7 m, and the surface percentage occupied by rocks was as high as 30% [Results from the Mars Pathfinder Camera, Smith et al. Science 1997]. The attenuation is accounted for with an effective imaginary permittivity that is proportional to the frequency^3 and rock radius^3 [Electromagnetic Wave Theory, Kong, 1986].

Surface clutter

The surface of Mars exhibits both large and small scales of surface roughness. The small scale of roughness is only significant at large backscattering angles, and thus will not influence the performance. However, the large scale will dominate and contribute to backscatter at off-nadir angles. The backscatter from this roughness could potentially mask the detection of subsurface layers. To be able to detect a subsurface layer, the layer reflection must overcome both the attenuation of the wave through the soil and the amount of backscatter occurring at the same range. For this case, even if the wave can penetrate, detection still may not be possible. The higher the frequency, the more the clutter signal level will be. This will impact the radar by limiting the operation of the radar to regions of Mars that are very smooth. This has to be analyzed and play a role in choosing an appropriate frequency.

Ionospheric dispersion and attenuation

The ionospheric attenuation and dispersion is most severe for frequencies close to the plasma frequency. As a result, the higher frequency radar is favored.

Faraday rotation due to Mars magnetic field

Recent MGS magnetometer data has pointed to much stronger magnetic field than previously expected for Mars. Although these strong magnetic fields are mostly localized, there are significant areas, especially, in the southern hemisphere, which have strong magnetic fields. The strong magnetic field in conjunction with a significant ionosphere can impact the operation of radars operating in the HF and VHF region (very similar to that expected on earth). To address this problem, instead of a single dipole, at very low mass penalty, one can include a cross-dipole to remove sensitivity to the Faraday rotation. This change in design, in addition to reducing risk, will have added science benefits which are presented in section 6.

Spatial resolution

The lateral spatial resolution of an orbiting radar will improve by increasing frequency. This will help in detecting and analyzing targets with smaller surface area. The depth resolution is defined by the bandwidth of the radar system. For higher bandwidth, one can get higher resolution depth profiles. In general, there is a connection between the bandwidth and the frequency through limitations in designing radar systems with high bandwidth/carrier ratio. As a result, higher carrier frequencies may be necessary to achieve high depth resolutions.

Except for items 1-3, an increase in the operation frequency has a positive impact on the performance. At higher frequencies, the radar coverage is reduced due to relatively higher surface roughness and subsurface attenuation. The choice of frequency has to be made such that the coverage is maximized subject to a cost function that accounts for the loss of spatial resolution.

Spacecraft accommodation considerations

In the design process, in addition to radar performance, the following spacecraft accommodation issues need to be considered:

1. Antenna size (-) [good]
2. Antenna efficiency (+) [good]
3. Required accuracy for spacecraft orbital parameters (+) [bad]
4. Spacecraft induced electromagnetic interference (-) [good]

Antenna size

Antenna size will decrease as the frequency increases.

Antenna efficiency

Antenna efficiency tends to be better at higher frequencies with lower relative bandwidth.

Spacecraft orbital parameter knowledge

Operation at higher frequency, or shorter wavelength, will require tighter constraints on the spacecraft orbital knowledge of position and orientation. The orbital knowledge is necessary for both radar operation and science data processing.

Spacecraft induced electromagnetic interference (EMI)

In general, EMI is better controlled at higher frequency in both radar-on-spacecraft and spacecraft-on-radar modes. Although this factor in relation to others mentioned above is not as sensitive to the frequency change. In terms of the frequency selection in the range of 10-50 MHz, this issue may be treated as neutral.

Scientific Return

Changing the design parameters of the SHARAD radar will in turn modify the scientific return capabilities. The trade-off of ground-penetrating radar implies a reduction of bandwidth (and thus poorer resolution) with a decrease in operating frequency. Alternatively, increasing the operating frequency will improve the resolution at the cost of poorer depth penetration and loss of coverage due to the increased clutter over increasing more percentage of Martian terrain. The factors outlined in the previous paragraphs show the advantages and disadvantages of increasing the operating frequency in terms of radar performance, but the scientific return of a higher resolution system should be evaluated to fully assess the capabilities of such an instrument. With a high frequency radar, the upper layers of the Martian crust could be mapped with finer resolution and possibly detect surface features that indicate the presence of water at greater depths. However, these higher resolution profiles may only be usable over few percent of Mars. So there is a need to balance the issue of the quality with the quantity.

In conclusion, we believe SHARAD will have the highest potential to meet its science objectives as stated earlier in this document after addressing the following issues:

1. optimize the operating frequency in terms of radar performance and scientific return
2. re-evaluate the choice of the bandwidth (related to operating frequency)
3. replace the current dipole antenna with a cross-dipole

5. Would uncertainties be reduced significantly by delaying until after MARSIS data are available?

3) If there are uncertainties in the technical ability to achieve the science objectives, would these be substantively reduced if MARSIS data were in hand?

Summary

Yes - both the European Mars Express MARSIS and the Japanese Planet-B PWS/LFA data would help. They should both provide information about background radiofrequency noise sources, and the LFA will provide noise data useful in designing low frequency sounders for rovers that could detect the water ice dielectric relaxation. They will also both provide data about the transparency and attenuation of the atmosphere and ionosphere, the reflectivity of the surface, and possibly about the properties of the subsurface. PWS has cross-dipole antennas that also will provide useful information about surface and volume scattering.

Discussion

MARSIS (Mars Advanced Radar for Subsurface and Ionospheric Sounding) on Mars Express to be launched by the European Space Agency (ESA) and the Plasma Wave and Sounder/Low Frequency Wave Analyzer (PWS/LFA) on Nozomi (Planet-B) already launched by the Japanese Institute of Space and Aeronautical Science (ISAS) are both expected to arrive at Mars in late 2003. Their respective instrument characteristics are listed in Table 1.

Table 1.

	MARSIS	**PWS**	**LFA**
Primary Mission	To investigate the surface and subsurface structure of Mars	To investigate the ionosphere of Mars	Frequency analyzer
Secondary Mission	To investigate the ionosphere of Mars	To investigate the surface property of Mars	N/A
Antenna	One dipole consisting of two 20 m elements One 7 meter monopole	Two dipole each consisting of two 25 m elements in cross-dipole configuration	Same as PWS
Transmitter frequency range	100 kHz – 5.5 MHz In surface sounding mode the frequency range is 1.3-5.5 MHz	50 kHz – 10 MHz In surface sounding mode the frequency range is 8-10 MHz	N/A
Pulse length	30-1000 µs	300 µs	N/A
Number of channels in surface sounding mode	Four 1 MHz bands with the ability to use any two within a single PRI	One 2 MHz band	N/A
Peak transmit power	10 W	600 W	N/A
Pulse repetition frequency	130 Hz	8 Hz	N/A
Dynamic range	45 db	120 db	120 db
Orbit	250 x 11000 km	300 x 51000 km	300 x 51000 km
Orbit incination	87 (near polar)	170 (near equatorial)	170 (near equatorial)

Mars global access	Close to global	Equatorial region	Equatorial region
Orbital period	7.5 hours	38.5 hour	38.5 hour
On-board processing	Yes	Unknown	yes
Ability to reject surface clutter	Yes	No	N/A
Polarimetric capability	No	Yes	Yes

Both PWS/LFA and MARSIS will study the Martian ionosphere (Matsumoto et al., 1998, Ono et al., 1998), and it is unknown how much data will be taken at night when subsurface sounding might be possible, although their use as a topography mapper (Oya and Ono, 1998) would suggest that night time operation might be expected (to get global coverage). As far as subsurface sounding is concerned, the relevant bandwidth is 1 MHz and above since even at night one cannot go through the ionosphere below that frequency. PWS/LFA is primarily designed as an ionospheric sounder and as a result is not optimized for subsurface or even altimeter operation. MARSIS on the other hand is primarily designed as a subsurface sounder having a stated "…primary objective to map the distribution of water, both liquid and solid, in the upper portions of the crust of Mars" with additional ionospheric sounding capability (Picardi et al., 2000).

Some thumbnail observations regarding MARSIS and PWS/LFA

- PWS/LFA are designed for ionospheric study. On PWS, there is an ALT mode which operates from 8 to 10MHz at 8 Hz PRF with a 600 W peak power. This is the only dedicated mode for Surface or subsurface sounding (which is relevant to this work).
- MARSIS can operate at two one-MHz bands at a given time at any of the 4 bands that it has from 1.3 to 5.5 for subsurface sounding at a PRF of 130 Hz with 10 W peak power. Accounting for the PRF difference (factor of 16) MARSIS has an equivalent power of 160W which means an overall power advantage of 5-6 db for PWS. 5-6 db advantage at 9 MHz may translate into an additional 250m penetration which is about 5% of MARSIS 5 km penetration depth.
- However, PWS due to its low PRF has essentially no ability to reject clutter, which it will have more than MARSIS, due to its higher frequency. As a result, it will not be able to interpret subsurface echoes as well as MARSIS can.
- PWS has onboard processing, compression, and a "program to optimize the data to fit the observation conditions" (Ono et al., 1998).
- PWS has a frequency band starting at 20 KHz, but it is not relevant to either MARSIS or the '05 radar because ionospheric experiment is not the primary goal of either of these two missions. The relevant subsurface sounding operation frequency at Mars, even during night, is above 1 MHz. So the band from 20 KHz to 1 MHz is purely used for ionospheric experiment.
- MARSIS has its band starting at 100 kHz to 5.5 MHz with the primary subsurface sounding band starting at 1.3 and ending at 5.5 MHz.
- PWS has a polarimetric set-up. With the recent discovery of strong magnetic field over some regions of Mars, the existence of the cross-dipole configuration has significantly increased the science return over all frequency bands.
- LFA will provide RF noise information down to 10 Hz that will be very useful in designing future low frequency electromagnetic systems to search for water and ice at kilometer depths.

Using radiowaves (radar) to sound the subsurface of Mars from orbit requires consideration of the following (as in the radar equation): frequency, transmitter power, antenna properties, media properties (including ionosphere and the soil & rock), background noise, receiver noise/sensitivity/dynamic range/bandwidth, multipathing, antenna location and orientation, as well as other mission concerns about data rate, weight, volume, spacecraft integration issues (such as instrument coupling and interference)..

Of this list (neglecting the mission considerations), the big unknowns are the background noise and the media properties. Both MARSIS and the LWA should provide information about background noise. Both MARSIS and PWS/LFA are designed to characterize the ionosphere properties. This leaves the media properties of the Martian subsurface materials: soil and rock. Both MARSIS and PWS are expected to receive reflections from the planetary surface. With a pair of cross-dipole antennas, PWS will receive polarization information that MARSIS will not have. Polarization data will allow better understanding of surface and volume scattering (Ulaby and Elachi, 1990) if Faraday rotation can be estimated accurately (this may be a significant challenge).

To measure the subsurface properties, the data processing and modeling will become very important, and the details expected for these are unknown. With dipole antennas, multipathing will be a major problem. Will reflections be from the subsurface below the orbital track or from the surface of that mountain off to the side? This was a significant issue in the Apollo Lunar Sounder Experiment (ALSE, 1972; Phillips et al., 1973; Porcello et al., 1974). Clutter (unwanted scattering) may also be a problem. If these issues can be resolved, then both MARSIS and PWS may provide information *within their frequency range* about subsurface attenuation mechanisms.

Radar energy is attenuated and lost on leaving the antenna by a variety of mechanisms. It is spread over the surface of a spherically expanding wavefront (like a balloon being blown up around the antenna) called geometric spreading loss as the energy density drops. It is transformed into heat by electrical conduction, electrochemical and dielectric relaxation mechanisms and by magnetic relaxation mechanisms. It is reflected, refracted, and diffracted in undesirable directions (meaning the transmitted power does not make it back to the receiver by any sensible path) by surface and volume scattering. It may follow multiple paths which cause small time (phase) shifts resulting in constructive and destructive interference at the receiver. Excepting geometric spreading, each of these loss mechanisms causes characteristic frequency dependence (dispersion) in the data (Olhoeft, 1984). The frequency range of MARSIS and PWS/LFA is too narrow to allow any useful expectations about the separation and identification of loss mechanisms. The presence of water also causes frequency dependence in radar data which can be exploited to determine water content (Olhoeft, 2000) even at low water concentrations, but that requires a well characterized radar system.

The Japanese Planet-B mission is expected to have a near equatorial orbit for the spacecraft, which will produce much redundancy in the data. Over a course of the seasons, the PWS could monitor significant changes associated with water transport and phase changes (vapor/liquid/solid) that would be a very useful scientific return.

6. What is the potential scientific return of the orbital radar currently being discussed?

Summary

A wideband HF/VHF radar (e.g. 10 MHz bandwidth at 20 MHz) will provide valuable information on the sub-surface structure of Mars. Radars with similar characteristics have provided valuable information on the stratigraphy of temperate ice [Arcone et al., 2000]. Radar data will supplement and complement hyperspectral data. We believe that inclusion of a high-frequency radar will provide significant scientific return and contribute invaluable information to design future sounding and imaging radars.

The distinct advantage of a radar at higher frequency than MARSIS is that it should be capable of better spatial resolution which would enable it to detect smaller features on the surface and subsurface. The countervailing disadvantage is that it would not be capable of deep penetration. If intended for an experimental exploratory mode, an HF/VHF sounding radar would provide an excellent complement to presently planned missions.

In summary, the major scientific returns can be given as:

1) Finding representative areas with higher likelihood of near-subsurface liquid water tables
2) Profiling the ice thickness of the polar region (or possibly 3-D imaging of the ice cap)
3) Characterizing the Mars magnetic field and ionosphere using polarimetric data
4) Polarimetric study of the radar return from the Mars surface if the Mars magnetic field can be assumed known through independent measurements (e.g. MGS magnetometer) and electron column density can be measured accurately. Two areas of special interest are the Tharsis “stealth region” which gives very little reflection using earth based radars (Muhleman et al., 1991, 1995; Grant and Schultz, 1996; Edgett et al., 1997, Edgett and Malin, 2000) and the areas with high residual magnetic field in the southern hemisphere.

The Importance of an Orbital Radar Sounder in Providing a Global Context in the Search for Subsurface Water

Terrestrial experience has demonstrated that the accurate identification of subsurface water and ice often requires the application of multiple geophysical techniques, which are most effectively employed at the surface. The principal attributes of such investigations (such as lander-based GPR) are their improved coupling to the surface (which minimizes electromagnetic signal loss) and their ability to identify variations in subsurface dielectric properties at high resolution (because of their proximity to the target).

But a strategy to search for water on Mars by proceeding directly to the use of high-resolution surface-based investigations has a significant drawback – for while such surveys may help determine the local distribution of volatiles to high precision, they provide no global context. This global context is important because, given the natural heterogeneity of crustal properties, the distribution of subsurface

H_2O is likely to differ substantially from one location to the next. Thus, while a high-resolution investigation might suggest the presence of a specific volatile target at a depth of 500 m at one location, it could well miss the opportunity – located only 20 km away – where that same volatile target was present at a depth of 100 m. Differences of this magnitude could well be critical to the success or failure of any follow-on drilling effort.

Therefore, given the fact that the Mars program doesn't have the resources to cover the planet with surface-based geophysical stations, how do we most effectively employ the limited number of surface- or airborne geophysical investigations that we will likely be able to fly?

Even with all its acknowledged limitations, an orbital radar sounder has one significant advantage over any other type of geophysical investigation that might be flown in that it can provide near global coverage (to a currently unknown and spatially variable depth) using a single spacecraft. Although, by itself, it may not be capable of making an unambiguous determination of the presence water or ice, it could potentially be used to eliminate significant areas of the planet from consideration and help identify the most promising local sites for further study. The "best" of these could then be targeted for local surveys (conducted by aerobots, dense local surface networks, rovers and other types of missions) to verify and map the distribution of volatiles at high resolution.

The value of higher frequency

In areas that support deeper radar penetration, higher frequencies than those used by MARSIS could provide higher-resolution profiles of the Martian subsurface. Such profiles would help deeper understanding of the subsurface structure of Mars. The radar data can be used to develop geophysical models or EM models of the Martian crust. These models will be invaluable in designing and optimizing future lander-based radar sounders and imaging systems. A major objective of a higher-resolution radar is to indicate areas that have higher likelihood of near-subsurface aqueous layers. The presence of an area-extensive dielectric layer in a family of profiles cannot be interpreted by itself as indicative of water, but it would provide strong evidence of a region worth more focused exploration.

In areas where there is minimal penetration, radar data can be used to estimate surface characteristics including roughness and dielectric properties. [[Are there any locations where there are sub-surface rocks or boulders that may act as point targets?]] If there are we can estimate velocity of propagation which is related to the dielectric constant that will provide some information about the material properties.

Polarimetric study of the Mars magnetic field and ionosphere

A major recent discovery on Mars is the detection of a strong but regionally localized magnetic field on Mars. MARSIS was designed under the assumption that Mars did not have a significant magnetic field, which implies that MARSIS may be “blind” under certain local circumstances. The existence of the magnetic field in conjunction with a strong ionosphere will cause Faraday rotation for HF and VHF radars operating on Mars. Faraday rotation can render the single-polarized reflections to be invisible to the radar, much as polarimetric eye glasses suppress solar reflections. Even at 20 MHz, Faraday rotation can be significant. Since it is frequency-dependent, it could reduce the potential resolution of any radar under the best of circumstances. The negative impact of Faraday rotation can be minimized by using a cross-dipole antenna rather than a single dipole (Section 4). The cross-dipole antenna would receive both polarizations. This would have two distinct advantages: 1)The polarization information along with the dispersion of the signal could be used to measure the Martian magnetic field independently; and 2) Combination of the signals received on both cross-polarizations would avoid signal fading.

In those areas in which Faraday rotation is significant, then MARSIS would encounter difficulty. This is likely to be true, for example, over parts of the southern hemisphere where the magnetic field is particulary strong (3000 nT or more). A radar enabled to receive both polarizations with a cross-dipole antenna would be able to operate normally in such regions.

Polarimetric study of the Mars Surface and Subsurface

Although it is not certain that in the presence of the Faraday rotation surface polarization information can be isolated, it should be addressed in the design of the instrument. If there is adequate SNR, it is possible to separate the Faraday rotation effects by taking advantage of already existing Mars Magnetic field values from MGS and an accurate estimation of the electron column density of the ionosphere.

Potential Value of Sounder to Polar/Climate Studies

One topic for which there is great potential for scientific return from a 20-Mhz orbital sounder is contributing to an improved understanding of the nature and evolution of the Martian polar regions - where, assuming loss characteristics similar to glacial ice, it may help to provide information on the total thickness, basal topography and internal structure of the layered deposits.

Among the specific questions that an orbital sounder might address are:

- What is the thickness, extent and continuity of the layers within the polar deposits?
- Is there any evidence of major uncomformities, or variations in the past extent of the caps, preserved within the polar stratigraphy or in the surrounding terrain?
- Is there evidence of internal deformation indicative of glacial flow?
- Is there evidence of basal melting, basal lakes, or peripheral ice deposits that may have been associated with subglacial discharges?

Due to its high inclination near-circular orbit, the polar regions will be covered with a dense grid of sub-satellite sounding tracks. One valuable contribution of such coverage would be the relatively high spatial and subsurface resolution of the Martian ice caps. The ice should admit reliable and geophysically useful radar penetration at HF/VHF frequencies, yielding depth profiles with maximal heritage to our present Earth-bound experience base. Dense spatial coverage will generate a pseudo-3D subsurface image of the region. Under favorable conditions, dense mutually coherent data could support 2D aperture synthesis, which would allow a demonstration of an holographic 3D portrayal of the near sub-surface structure of the ice caps.

Unraveling the complex geologic and climatic record preserved in the layered deposits would be greatly aided by the identification of areally-extensive stratigraphic horizons that could serve as temporal benchmarks (i.e., strata that might be targeted by future in-situ, or sample-return, dating efforts). However, even with assistance of high-resolution MOC images, it has proven enormously difficult to establish layer continuity on exposed scarps, even between neighboring troughs. In contrast, the ability of a radar sounder to identify high-contrast layers (such as those created by volcanic ash deposits) offers the potential for identifying such horizons over the extent of the cap.

While a polar-orbiting radar sounder appears to offer considerable promise for polar investigations, the inherent difficulty of discriminating between the dielectric properties of ice, embedded dust, and a polar basement of unknown lithology may introduce sufficient uncertainty in the interpretation of the radar data that a combination of other geophysical techniques and/or in situ drilling may ultimately be required for its validation.

The Value of a Negative Result

In discussing the ability of the SHARAD instrument to detect liquid water, much of the concern has focused on how other substances or conditions within the subsurface might cause a similar lack of penetration, precluding an unambiguous identification. Nevertheless, our models clearly show that if liquid water is present in significant concentrations in the volume being investigated, a suggestive return will result. This means that if the sounder gets NO suggestive returns anywhere, or gets them from just a few percent of all the areas it observes, this lack of a return implies (to a high level of confidence) that near-surface liquid water is not present at those locations. This negative result would still be a tremendously important finding because it would help eliminate many areas from consideration for future near-surface investigations. This ability to eliminate and prioritize potential landing sites for further study underscores the importance of orbital sounding as a vital precursor to landed missions.

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APPENDIX 1:
Simulation of Ground-Penetrating Radar/Orbiter.

The scientific return of a GPR on Mars is highly dependent on the stratigraphy and lithology of the subsurface layers. Since the electrical properties governing scattering and propagation of these layers are, to a large extent, unknown, predicting the performance of a radar will involve extensive simulations over a wide range of models from simple two to three layer configurations to many-layer configurations of different geological locations. The results shown in this appendix represent a few possible models to facilitate a better understanding of what specifics problems may be encountered. Excluding the receiver minimum detectable signal, the sources of attenuation, reflection, and clutter are given below along with a general condition for detection.

Sources of attenuation (other than constant spherical spreading loss)

1. Transmission and reflection off intermediate layers (dependent of the number of layers and dielectric contrasts)
2. Attenuation due to soil properties (dependent on the soil type, magnetic content)
3. Attenuation due to volume debris (dependent on the size and distribution of buried rocks, accounted for in an effective permittivity)

Sources of refection (gain, other than antenna and system properties)

1. Reflection coefficient of desired layer (dependent on the dielectric contrast of the layer)
2. Surface Roughness (dependent on the r.m.s. slope the reflection, ideally specular)
3. SAR Processing (dependent on aperture length, sampling rate, and surface roughness)

Sources of clutter

1. Scattering off volume debris (dependent on the size of buried rocks)
2. Multiple scattering off intermediate layers (dependent on dielectric contrasts)
3. Off-nadir rough surface backscatter (dependent on the r.m.s. slope)
4. Noise (dependent on receiver bandwidth)

Condition for detection – to be able to detect a subsurface layer, the sources of reflection minus the sources of attenuation must be greater than the sources of clutter.

For an orbiter radar, where the distance of the radar is much greater than the depth of penetration, the transmission and reflection of the incident pulse can be approximated as a plane propagating normally through a layered media. This one-dimensional response is calculated by representing the subsurface as a set of transmission lines (each with a complex propagation constant and characteristic impedance corresponding to the electrical properties of the layer) and calculating the complex reflection coefficient versus frequency. The three-dimesional return is obtained by: 1) generating the 1-D plane wave response; 2) multiplying by the antenna pattern and surface backscatter and time scaling for responses from off-nadir angles; 3) convolving with a surface random variable; and 4) applying spherical spreading loss and other system parameters.

Simulation 1

The first simulation shows the response from a three-layer medium containing a layer of ice. The model parameters are shown in Table 1, and the transmitted signal is a 20 MHz center frequency, 10 MHz bandwidth Gaussian pulse. The electrical properties were determined using simple density and linear mixing formulats [Electrical Properties of Rocks, in Physical Properties of Rocks and Minerals, Olhoeft, G. R., 1989]. The simulation results shown in figures 1 and 2 show the radar response for surface roughnesses of 0.015 and 0.007 rad. In the first simulation, it is clear to see that without SAR processing it would be impossible to detect the third layer due to the off-nadir clutter. For the geometric optics backscatter approximation, it can be shown that the clutter response will fall off by a rate inversely proportional to the r.m.s. surface roughness. Figure 2 supports this relationship by showing a detectable layer when the roughness is reduced.

Table 1. Three-layer configuration.

					ε at 20 MHz	
thickness	%porosity	%iron oxide	saturation	phase	ε′	ε″
400km*	100	0	-	-	1.0	0.00
200m	50	15	-	-	3.0	0.02
200m	30	15	80	ice	5.4	0.05
-	20	15	-	-	5.8	0.07

*first layer is the height of the radar.

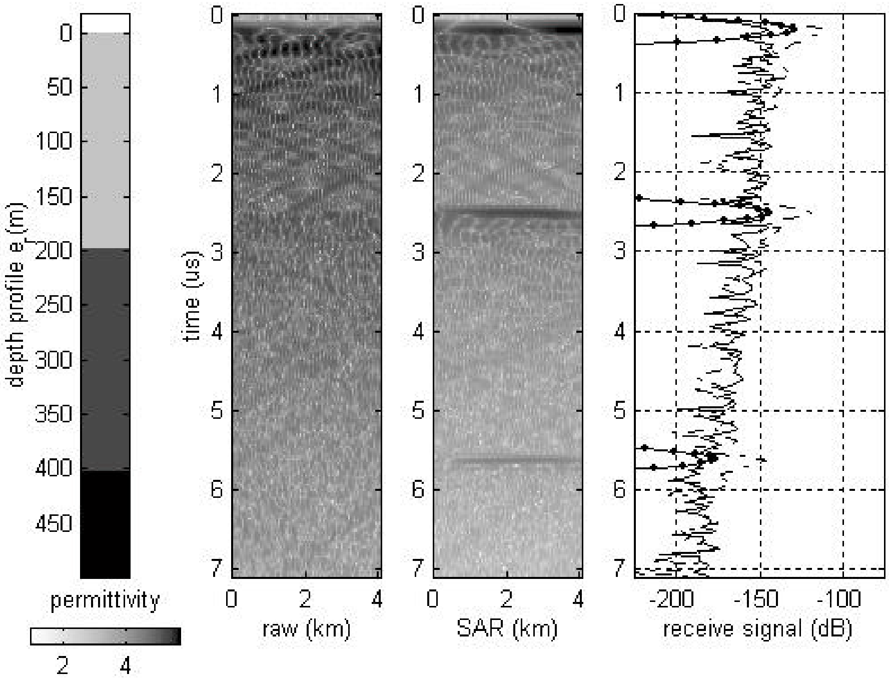

Figure 1. Simulation results from model 1 with an r.m.s. surface slope of 0.015 rad. From left to right are shown the permittivity depth profile, unprocessed image, SAR processed image, and dB plots

normalized to transmit power for (solid-dot) ideal, no surface clutter response, (solid) raw data, (dashed) SAR processed data.

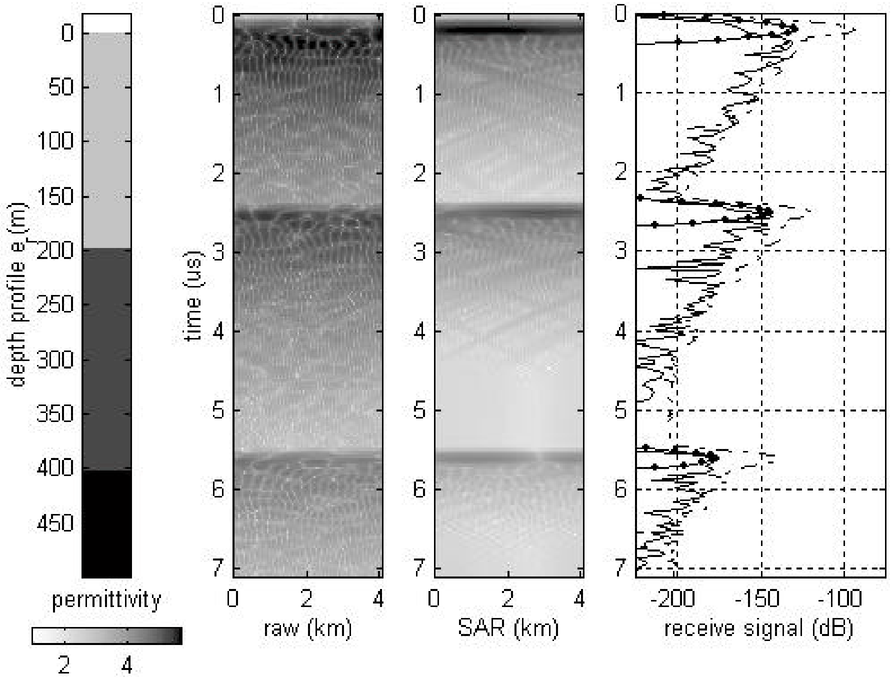

Figure 2. Simulation results from model 1 with an r.m.s. surface slope of 0.007 rad.

Simulation 2

The second simulation, model shown by Table 2, replaces the layer of ice with a slightly denser soil. The result in figure 3, shows that the reflection off of the dense layer is very similar to that produced by the layer of ice. It becomes apparent that even if the density was kept constant and the ice was removed, the radar response would still be very similar to that shown by model 1.

Table 2. Three layer configuration.

					ε at 20 MHz	
thickness	%porosity	%iron oxide	saturation	phase	ε′	ε″
400km*	100	0	-	-	1.0	0.00
200m	50	15	-	-	3.0	0.02
200m	25	15	-	-	5.2	0.06
-	20	15	-	-	5.8	0.07

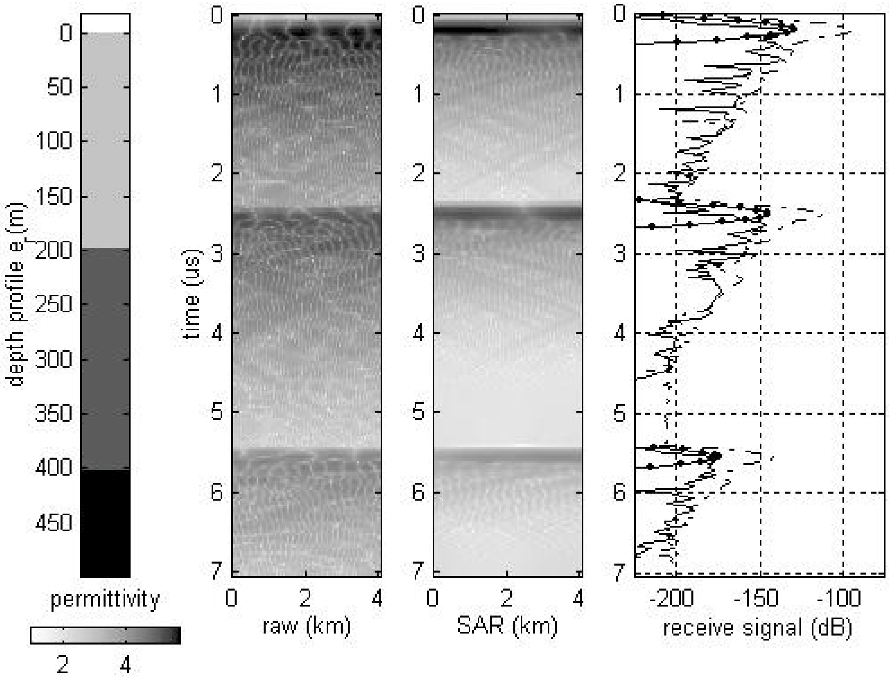

Figure 3. Results from model 2 (without ice), 0.007 rad surface roughness.

Discussion

The simulations above show the response of a three-layer model. If chirp radar is used, an additional compression gain of approximately 200 (23 dB) could be expected and must be added to the received signal responses shown. This would place the normalized surface response at approximately -70 dB and the third interface at approximately -120 dB. Noise calculations show the minimum detectable signal is approximately -130 dB. Using this value as a lower bound, it can be seen that the third layer in the above simulations will be detectable with a 10 dB signal-to-noise (SNR) ratio. This SNR may seem low, but it should be pointed out that the dielectric contrast of the third interface is only about 10% corresponding to a reflection coefficient of about -30 dB. If this contrast were increased, say for the extreme case of a layer of water, and the attenuation was similar to the above simulations, it may be possible to see a reflection as deep as 1 km.

APPENDIX 2: SCIENCE OBJECTIVES FOR THE MRO (reprinted verbatim from the SDT Report)

SCIENCE OBJECTIVES FOR THE MRO

The Mars Exploration Program has adopted a “Follow the Water” strategy, which provides the crosscutting theme through the Mars Exploration Program’s four main areas of emphasis: Life, Climate, Geology, and Preparation for Human Exploration of Mars. The SDT focused on the first three of these areas, which motivate the core science investigations. The “Follow the Water” strategy is very ambitious, and any single mission can accomplish only a part. Also, the degree of progress that can be made in any one area, no matter how high its scientific priority, often depends critically on the progress of instrument technical development. This is particularly important for the MRO mission as described by the Project to the SDT, as it appears to have a doable, but still challenging schedule for spacecraft and payload development, assembly, test and launch. Furthermore, although the SDT did not discuss mission budget in any detail, there are concerns that the funding available cannot support substantial instrument technical development. The MRO budget portion for the science payload appears to have been taken from the ’03 MSO study (adjusted for inflation). That study emphasized flight-proven instrument design and hardware, due to the even more demanding schedule required for launch in 2003.

With these potential constraints in mind, the SDT has divided the recommended science objectives for the MRO mission into two categories. The SDT recommends that *the core objectives (Group I) must be addressed in a significant way by any payload selected for MRO.* However, the SDT believes that instruments addressing these core scientific objectives do not require the full capabilities allocated for payload in the MRO reference mission. Within the remaining resources, *NASA should consider selection of investigations that address additional high priority scientific objectives (Group II).*

The scientific objectives recommended for the MRO mission are then:

Group I:

1. Recover the MCO atmosphere and climate science objectives:
    - Characterize seasonal cycles and sample diurnal variations of water, dust, and carbon dioxide to understand processes of present and past climate change.
    - Characterize global atmospheric structure, transport, and surface changes to elucidate factors controlling the variable distributions of water and dust.

2. Search for sites showing evidence of aqueous and/or hydrothermal activity:
    - Search for localized areas showing past aqueous mineralization.
    - Observe detailed geomorphology and stratigraphy of key locales to identify formation processes of geologic features suggesting the presence of liquid water.

3. Explore in detail hundreds of targeted, globally distributed sites:

- Characterize in detail the stratigraphy, geologic structure and composition of surface features to better understand the formation and evolution of complex terrain.
- Distinguish processes of eolian and non-eolian transport and surface modification.

Group II:

1. Detect the presence of liquid water and determine the distribution of ground ice in the upper surface, particularly within the near-surface regolith.

2. Provide atmospheric observations in addition to the MCO capabilities (i.e., PMIRR and MARCI Wide Angle) to further define atmospheric structure and circulation.

3. Characterize the gravity field in greater detail to understand better the geologic history and structure of the crust and lithosphere.

4. Explore additional ways of identifying sites with high scientific potential for future Mars landed investigations.

(The listings within Group I and Group II do not imply priority.)

The strategy outlined above is the recommendation of the SDT. However, it was not unanimous, in part because there are at least two views of what reconnaissance means in the context of an ’05 Mars mission. One view is that it should be “reconnaissance in force”, in the sense that the mission and spacecraft resources are fully dedicated to one or two primary investigations (e.g., ultra-high-resolution imaging or subsurface sounding). In this view, one attempts to bring to closure one or two primary scientific objectives, as completely as can be achieved from orbit (within the foreseeable future).

The second—and majority—view of the SDT was that an ’05 orbiter mission should be one of exploration and discovery in a few carefully chosen areas, rather than detailed characterization in support of a single objective, even as the mission focuses on a single theme (“Follow the Water”). There is much that we do not know or understand about Mars, and a significant effort in a few well–chosen, high priority areas was judged by a majority of the SDT to be most likely to advance substantially our understanding of Mars. Furthermore, a cross-disciplinary MRO mission will provide—together with 2001 Mars Odyssey and ’03 Mars Express—the critical data needed to define such highly focused “closure” missions, each of which might well require the equivalent of the MRO spacecraft and mission resources, as part of the ongoing Mars Exploration Program.

In summary, the SDT recommends that the MRO mission address each of the Group I objectives and, as resources permit, one or more of the Group II objectives.