ANALYSIS OF THE POTENTIAL OF A MARS ORBITAL GROUND-PENETRATING RADAR INSTRUMENT IN 2005

January 28, 2001

A White Paper

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Note: This report represents the analysis completed by the above team over a period of about two months, as input to the '05 SDT. We recognize that documents such as this are never final, and that this work will likely need to be refined (possibly by other authors) during 2001. However, in order for the information to be in time to make a difference, our revisions must be closed with this version. For future reference, the final electronic file of this report is named Radar_White_Paper_v10.doc.

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1. Executive Summary

Radar sounding on Mars is one of the critical measurements required by NASA's strategy of "follow the water". The MARSIS instrument, which will be included on the Mars Express mission in 2003 will be a first step towards acquiring these data. The purpose of this report is to assess the scientific and technical justification of including a second radar sounder on the '05 Orbiter to extend the results of MARSIS. Note that as of this writing, a radar sounder is not part of the baseline plan for the '05 Orbiter.

During November and December 2000, a multi-disciplinary team assessed a specific set of questions (see Appendix 1) related to this opportunity. These results constitute input to the science definition team for this mission.

Summary Conclusions

1. Science of water on Mars. Geomorphic evidence and theoretical arguments suggest that the Martian crust is water-rich and may possess a complex stratigraphy of saturated and unsaturated frozen ground, massive segregated bodies of ground ice, liquid groundwater, and gas hydrates within the top 10 km. As recently summarized by MEPAG, assessing the 3-dimensional distribution and state of water in the Martian crust is the common thread and one of the primary goals of the Mars exploration program. Analysis of the science of subsurface water on Mars is contained in Section 3 of this report.
2. Water detection using radar sounding. An orbital radar sounder provides a unique ability to map the subsurface distribution of water on a global basis with a single spacecraft. Such a reconnaissance would likely also yield significant new insights regarding the subsurface structure and lithology of the crust, including the nature of the polar layered deposits. Although the unambiguous identification of a specific volatile target is probably not possible using orbital sounding alone, it provides the only approach for achieving global coverage of this important data type. This analysis is contained in Section 4 of this report.
3. MARSIS. MARSIS, the radar sounder that will fly on Mars Express in 2003, will attempt to sound as deep as 5 km, with a depth resolution of 50-80 m and a horizontal footprint of 5-10 km. At a minimum, a MARSIS-like instrument on the 2005 Orbiter would benefit from the low-eccentricity orbit and increased data volume, as well as from possible improvements in spacecraft accommodation and electromagnetic compatibility, as compared with Mars Express. This could result in improved science return in terms of coverage, maximum detection depth, sensitivity and interpretability of data. This analysis is contained in Section 5 of this report, as well as Appendices 2 and 3.
4. Second Generation Radar Sounder. A second-generation radar sounder can be designed to obtain both high vertical resolution (10-20 m) soundings of the upper 1 km (with a footprint size as small as 1 by 3 km) and equal, or improve upon, the deep sounding capability of MARSIS using a single instrument. A radar including antenna and signal processing algorithms can be developed to maximize information return from the upper 500-1000 meters of Martian soil. This analysis is contained in Sections 5-7 of this report.
5. 2005 Orbiter. There are sufficient mass, power and data volume resources to accommodate a second-generation radar sounder on the 2005 orbiter. Issues such as mechanical accommodation, dynamic stability, and electromagnetic compatibility need to be resolved. Although issues such

as mechanical accommodation, dynamic stability, and electromagnetic compatibility need to be resolved, all appear tractable. . This analysis is contained in Section 8 of this report.

6. Programmatic Issues. Flying a radar sounder in the 2005 opportunity is compatible with Mars programmatic goals. It continues the probing started with MARSIS to "follow the water" by directly detecting ice and possible aquifers, with an increased likelihood of success due to the mission design. The capability to probe the upper 1 km at high resolution allows testing of hypotheses of recent shallow water reservoirs, and feeds forward to characterization and selection of possible sites for drilling experiments in 2007 and beyond. In addition, the expected improvements in orbital characteristics and data volume in '05 provide an opportunity for substantial advances in deep sounding capability. While a second-generation radar sounder will benefit from MARSIS design heritage, the design of a 2005 sounder cannot benefit from MARSIS data due to the close consecutive launch opportunities. Consequently, most risks associated with uncertainties in the Mars environment (ionosphere, attenuation in the crust, nature of interfaces) will apply to both MARSIS and a 2005 sounder.
7. Technology Development. Technology for implementing a radar that operates in four sub-bands in chirp mode already exists. Four element antenna for this radar must be evaluated for determining the mutual interaction between sub-band antenna elements. Step-frequency radars to support variety of military and commercial applications have been developed. Technologies developed in support of these can be readily adopted for a dual-mode radar, but some of the hardware may need to be space qualified. . This analysis is contained in Section 9 of this report.

Summary Recommendations

1. We recommend inclusion of a coherent radar sounder on the 2005 Mars Reconnaissance Orbiter 2005. The sounder should operate in two modes: high-resolution (~20 m) for collecting data on subsurface features to depths approaching 1 km, and low-resolution (~100 m) for collecting data for depths beyond 1 km. These dual-mode data will both complement and supplement those from MARSIS for imaging sub-surface features.
2. We recommend that NASA initiate a study to define an optimum system including signal processing algorithms with existing technologies.

2. Introduction

The search for water is a primary focus of Mars exploration. At the surface of Mars, water is present only as ice in the polar ice caps and in trace quantities in the atmosphere. In order to discover liquid water, we will need to search in the subsurface. The abundance and distribution of water (both as ground ice and groundwater) have important implications for understanding the geologic, hydrologic, and climatic evolution of the planet; the potential origin and continued survival of life; and the accessibility of a critical *in situ* resource for sustaining future human explorers.

A critical investigation identified by MEPAG is subsurface sounding using ground penetrating radar. The first measurement towards this investigation will be the MARSIS radar sounder, which will be flown on the Mars Express spacecraft in 2003.

The purpose of this document is to evaluate the scientific and technical merits of placing a second radar sounder on the 2005 Orbiter. This analysis was initiated at the beginning of November, 2000, and is intended to supply input to the Science Definition Team for the 2005 Orbiter by approximately the first of 2001. The charter for this assignment is included as Appendix 1 of this report.

If any reader has follow-up questions, he/she is encouraged to contact anybody listed on the cover sheet of this report.

3. Overall Scientific Objectives of Orbital Radar Sounding

A. Introduction

The basis for an Orbital Radar Sounder -

The major goals outlined by the MEPAG focus on determining: 1) whether life ever arose on Mars; 2) the climate history of Mars; 3) the evolution of the interior and surface of Mars; and 4) how best to prepare for the human exploration of Mars. The common theme associated with each of these goals relates to the occurrence, distribution, and form of water on Mars. As summarized below, the importance of resolving the water inventory of Mars is reflected in the primary objective and (in all but one instance) the highest priority investigation and required measurement for each of these four MEPAG goals. Text in boxes below is directly quoted form the prioritized MEPAG document, and reference numbers refer to the source.

I. GOAL: DETERMINE IF LIFE EVER AROSE ON MARS

A. Objective: Determine if life exists *today*.

1. *__Investigation:__* *Map the 3-dimensional distribution of water in all its forms.* Zones of liquid water in the subsurface provide the most likely environments for extant life on Mars. In the absence of life, such environments could also sustain pre-biotic chemistry of interest for understanding the origin of life on Earth. **Requires global remote sensing of water in all its forms to identify the locations, phases, and, if possible, temporal changes in near-surface water budgets.**

__Measurements:__

a. Global search and mapping of water to 5.0 km depth at a horizontal spatial resolution of 1.0 km and vertical resolution of 400 m; must be able to distinguish ice and liquid water.

II. GOAL: DETERMINE CLIMATE ON MARS

A. Objective: Characterize Mars' Present Climate and Climate Processes.

1. *__Investigation:__* *Determine the processes controlling the present distributions of water, carbon dioxide and dust.* Understanding the factors that control the present annual variations of volatiles and dust on Mars is a necessary first step to determining to what extent today's processes have controlled climate change in the past. Requires, in priority order: 1) global mapping of the time-varying three-dimensional distributions of dust, water vapor, carbon dioxide, thermal state, and radiative forcing of the atmosphere, surface and near-subsurface over at least one annual cycle; 2) landed observations of the exchange of volatiles and dust between the surface and atmosphere on daily and seasonal time scales.

__Measurement:__

b. Detect near-surface (< 100 m) and deep (100 m – 5 km) occurrences of liquid water; map global presence at scales equal to, or better than, 10 degrees longitude by 30 degrees latitude. Determine depths to ± 10 m for near surface water, ± 100 m at greater depth.

c. Detect subsurface ice layers, delineating depth with precisions of 100-200 m as deep as 5 km, at horizontal scales of a few hundred kilometers.

III. GOAL: DETERMINE THE EVOLUTION OF THE SURFACE AND INTERIOR OF MARS ("Geology")

A. Objective: Determine the nature and sequence of the various geologic processes (volcanism, impact, sedimentation, alteration etc.) that have created and modified the *Martian crust and surface*.

1. *Investigation:* ***Determine the present state, distribution and cycling of water on Mars.*** Water is the critical limiting resource for the development and sustenance of life and for future human exploration. **Requires global observations using geophysical sounding (radio or radar).**

Measurements:

a. Orbital remote sensing using sounding to detect water at spatial scales of approximately 100 m and to a depth of several kilometers.

b. Orbital and/or aerial platform remote sensing using to search for subsurface water and to determine its physical state on spatial scales ranging from 100 km (from orbit) to 100 m (from aerial platforms).

6. *Investigation:* ***Determine the large-scale vertical structure of the crust and its regional variation. This includes, for example, the structure and origin of hemispheric dichotomy.*** The vertical and global variation of rock properties and composition places constraints on the distribution of subsurface aquifers and aids interpretation of past igneous and sedimentary processes. **Requires geophysical sounding from orbiters and surface systems, geologic mapping, in-situ analysis of mineralogy and composition of surface material, returned samples, and seismic monitoring.**

IV. GOAL : PREPARE FOR HUMAN EXPLORATION

A. Objective: Acquire Martian environmental data sets.

3. Investigation: Understand the distribution of accessible water in soils, regolith, and *Martian groundwater systems.* Water is a principal resource to humans. Requires geophysical investigations and subsurface drilling. Can also be met by sample analysis.

Measurements:

a. Map the Martian subsurface for liquid water reservoirs.

b. Obtaining the vertical distribution of permafrost, water ice and liquid water is essential to understand the requirements for drilling equipment that will be used to penetrate these layers.

B. Discussion of MEPAG Document

An orbital radar sounder has the potential to penetrate beneath the surface of Mars and should be highly sensitive to the presence of liquid water as well as being capable of defining coarse-scale stratigraphy within the Martian crust. As such, an orbiting radar sounder could accomplish many of the critical measurements outlined above and should be considered as a high priority candidate for flight on an upcoming mission. Post-MARSIS instrument design concepts are responsive to the stated measurement requirements, including penetration to depths of ~5-10 km with the ability to resolve features on the scale of 0.1 km vertically. Somewhat lesser capabilities (e.g., penetration to

~3-5 km depth with vertical resolution of ~ 0.4 km) would still permit achieving a number of important goals.

C. Expected Volatile Stratigraphy of the Martian Crust

A summary of the expected state and distribution of water and other volatiles on Mars follows and is based on current models and observations. This overview is presented as context for understanding the need for global measurements using an orbital radar sounder and as the framework for subsequent definition of specific science questions related to the stated MEPAG priorities.

1. Distribution of H_2O. To a first order, subsurface conditions on Mars are expected to resemble those found in cold-climate regions on Earth, particularly the unglaciated, continuous permafrost regions of Antarctica, Siberia, and North America. This similarity is likely to extend to an equivalent level of geologic complexity and spatial variability in such characteristics as lithology, structure, stratigraphy, porosity, ice content, and mechanical and thermal properties.

Current mean annual surface temperatures on Mars range from ~154 K at the poles to ~218 K at the equator (±5 K), with radiogenic heating expected to result in increasingly warmer temperatures at depth. The region of frozen ground defined by this thermal structure is known as the cryosphere, whose depth z, at any location, is given by

$$z = \kappa \frac{T_{mp} - T_{ms}}{Q_g} \tag{1}$$

where T_{ms} is the mean annual surface temperature, T_{mp} is the melting temperature of ice at the base of the cryosphere, Q_g is the geothermal heat flux, and κ is the column-averaged thermal conductivity (Fanale 1976; Rossbacher and Judson 1981; Kuzmin 1983; Clifford 1993).

Substituting the present best estimates of mean annual surface temperature (154 K – 218 K), geothermal heat flow (~30 mW m^{-2}), and melting temperature (252-273 K) into Eq. (1), we find that the present thickness of frozen ground on Mars should vary from ~2.3 km – 4.7 km at the equator to ~6.5 km – 13 km at the poles (Fig. 1; Clifford and Parker, 2000). However, natural variations in crustal heat flow and thermal conductivity are likely to result in significant local departures from these predicted average values.

At the Martian surface, the low relative humidity of the atmosphere means that ground ice is thermodynamically unstable at latitudes equatorward of ~40^{o} – leading to its sublimation at a rate that is dependent on the mean annual surface temperature, as well as the local thermal and diffusive properties of the crust. Depending on the nature of these properties, their variation with depth, and the potential for replenishment from any deeper reservoir of subpermafrost groundwater, these factors may result in local depths of desiccation at low-latitudes that range from centimeters to as much as a kilometer -- with the potential for significant and complex variations in saturation state beneath the sublimation front (Fig. 2; Clifford, 1998). Such uncertainties preclude any reliable theoretical or geomorphic prediction of the local presence and subsurface distribution of ground ice below the seasonal skin-depth.

Ground ice may also be present as massive segregated deposits in the northern plains – an expectation based on the possible former existence of a Noachian ocean, and the geomorphic evidence for extensive and repeated flooding by Hesperian-age outflow channel activity. As a result, the volatile stratigraphy of the northern plains is likely to be quite complex, having been built up through multiple episodes of flooding, freezing, sublimation, and burial. This complexity has undoubtedly been compounded by local differences in hydraulic and geologic evolution arising from impacts, volcanism, tectonism, and other processes, as well as by extreme climatic fluctuations associated with the chaotic evolution of the planet's obliquity (Touma and Widom, 1993; Laskar and Robutel, 1993; Jakosky et al., 1995). While the resulting fine-scale structure of the crust is expected to exhibit considerable heterogeneity, in many areas the bulk properties of the uppermost ~0.1 km – 1.0 km are likely to be dominated by multiple, overlapping deposits of water ice – with individual flows ranging from meters to many hundreds of meters thick (Fig. 3).

If the Martian inventory of water exceeds what can be stored as ice within the pore volume of the cryosphere, then any excess will be stored as groundwater, saturating the lowermost porous regions of the crust. Given a large-scale permeability of the planet's crust comparable to that of the Earth and the apparent lack of recent precipitation, the influence of gravity should result in a groundwater system that is effectively in hydrostatic equilibrium – except where it may be locally perturbed by tectonic, seismic or thermal processes. Because of the low values of crustal porosity expected at depth, comparatively little water is required to produce a groundwater system of substantial extent. Thus, if a subpermafrost groundwater system is present on Mars, it is expected to underlie much of the planet's surface.

Because the distribution of ground ice is expected to follow the thermal structure of the crust, while the global groundwater table is expected to conform to a surface of constant geopotential, the vertical distance separating these subsurface reservoirs of water and ice is expected to vary considerably. The intervening unsaturated zone will be maximized in regions of high elevation and minimized (or absent) at lower elevations (Fig. 4). Within the unsaturated zone, the presence of a geothermal gradient is expected to give rise to a low-temperature hydrothermal convection system of rising vapor and descending liquid condensate that may have lead to the development of perched water tables and the geochemical evolution of the underlying groundwater into a highly mineralized brine (Clifford, 1993).

The preceding discussion suggests that the occurrence of liquid water on Mars today is restricted to depths of several kilometers or more (except, perhaps, where it may occur in association with local geothermal anomalies). This belief has recently been challenged by Malin and Edgett (2000), who have identified features in high-resolution MOC images that they interpret as having originated from recent (within last ~10^7 years, and possibly still active today) episodic discharges of near-surface liquid water. Although extremely rare (being found in less than 1% of all MOC images taken to date), these "seepage" features are found on exposed scarps in both the northern and southern hemispheres within the latitude band of 30^o – 70^o that occur preferentially (by a factor of 2-to-1) on poleward-facing slopes. While the true nature and age of the Malin and Edgett "seepage" features continue to be topics of intense debate, the potential implications of a fluvial origin require that they not be discounted.

2. The potential occurrence and distribution of gas hydrates and liquid CO_2. Gas hydrates may also exist on Mars. Hydrates are formed when hydrocarbons and other gases (like CO_2 and H_2S) are concentrated under condition of high pressure and low temperature in the presence of H_2O – where they can become stabilized by Van der Waals bonding within the cubic crystalline lattice of water ice molecules. On Mars, methane may have been produced by biotic (Farmer, 1996; Fisk and Giovannoni, 1999; Max and Clifford, 2000) and/or abiotic (Wallendahl and Treiman, 1999) processes. As the internal heat flow of Mars has declined with time, the resulting downward propagation of the freezing-front at the base of the cryosphere would have incorporated any subsurface methane that exists as hydrate. These hydrates could occur in concentrations ranging from a dispersed contaminant, to massive deposits (Max and Clifford, 2000).

Several workers (e.g., Miller and Smythe, 1970; Milton, 1974; Kamatsu et al. 2000; Kargel et al. 2000) argued that substantial amounts of CO_2 hydrate might also be present in the Martian subsurface. The molecular structure of CO_2 hydrate is essentially identical to methane hydrate, with the exception that CO_2 substitutes for CH_4 as the guest molecule in the crystalline lattice of water ice (Miller and Smythe, 1970; Sloan, 1997). The stability field of CO_2 hydrate is also similar, but shifted to slightly shallower depths – extending from ~5 m (corresponding to a confining pressure of ~50 kPa) at 200 K to a maximum depth defined by the location of the 283 K isotherm. The most probable mechanism by which such deposits could have formed is by the progressive cooling and freezing of CO_2-saturated groundwater.

In addition to gas hydrates, several recent studies have argued that the expected pressure and temperature conditions in the Martian subsurface also permit the stable existence of liquid CO_2 – in amounts that may range from small inclusions to aquifer-like reservoirs that may have played a role in the genesis of the outflow channels (e.g., Hoffman, 2000). However, while it is possible to identify a P-T environment in the Martian subsurface where liquid CO_2 would be stable if emplaced after that environment had formed, it appears difficult to imagine an evolutionary scenario by which aquifers of liquid CO_2 could have initially formed and survived to the present day. If, however, liquid CO_2 is currently present in the subsurface, it appears that it will most likely occur as inclusions and localized pockets.

D. Summary of Potential Subsurface Targets and Associated Scientific Objectives

The search for subsurface water has become a primary focus of Mars exploration. Its abundance and distribution (both as ground ice and groundwater) have important implications for understanding the geologic, hydrologic, and climatic evolution of the planet; the potential origin and continued survival of life; and the accessibility of a critical *in situ* resource for sustaining future human explorers.

For these reasons, the principal goal of the Mars science, astrobiology, and the HEDS programs is to determine the 3-D distribution and state of subsurface H_2O, at a resolution sufficient to permit reaching any desired volatile target by drilling. Additional objectives include the identification of other volatile substances (such as gas hydrates and liquid CO_2), local and regional variations in subsurface structure and lithologies, and any compositional information that can be deduced from the character and penetration depth of the returned signal (e.g., the presence of iron oxide, carbonates, etc.).

The H_2O mapping requirements identified by MEPAG differ by subgroup, with a maximum desired sounding depth of 10 km. Although the MARSIS instrument aboard Mars Express may yield first order information regarding the distribution of water and ice in the crust within the depth range of 1 - 5 km, its ability to detect H_2O at greater or shallower depths is limited. From the perspective of identifying volatile targets that might be accessed by drilling in the near-future, the most desirable improvement in a 2nd generation radar sounder would be the identification of ground ice and groundwater at shallower (<1 km) depths – without sacrificing a deep-sounding capability equivalent to, or better than, MARSIS. To make targeted drilling investigations practical, this will require vertical and horizontal resolutions of approximately 20 meters and 1000 meters, respectively. The technology required for development of a radar that can accomplish this task appears to be in-hand and could likely be implemented in accordance with the schedule dictated by the Mars 2005 Orbiter mission.

Regardless of the success of MARSIS, the inclusion of a radar on the Mars 2005 orbiter with the above capabilities would enable a major increase in our understanding of the role of water on Mars with respect to the goals defined by MEPAG. Such data would enable significant advances in knowledge relevant to answering a wide range of specific questions related to the life, climate, geology, and future human exploration of Mars. These questions can be grouped in several topical areas and are described in more below.

1. Saturated/Unsaturated Frozen Ground: The distribution of frozen ground on Mars is by definition coextensive with the cryosphere; however, local variations in mean annual temperature, geothermal heat flow, and the thermophysical and diffusive properties of the crust, are likely to result in complex stratigraphic and geographic variations in saturation state – particularly within the top $\sim 10^2$ m – 10^3 m of the crust (e.g., Fig. 2). Of particular interest is the extent of equatorial and mid-latitude desiccation due to the sublimation of ground ice.

Primary science questions related to this target:

i. How does the depth of desiccation vary geographically?
ii. How does the saturation state of the crust vary stratigraphically and geographically beneath the shallowest occurrence of ground ice?
iii. How large is the variability of both of the above at m- to km- size scales?
iv. What are the temporal changes in the near-surface water budgets from summer to winter, and from year to year over the lifetime of the mission?

Related technical issues:

To what extent can an orbital radar sounder assess the saturation state (or contrasts in the saturation state) of the crust?

What is the plausible highest spatial/volume resolution of a sounder as a function of depth?

What constraint does this resolution place on our ability to assess a minimum and maximum volume-averaged saturation state?

Are there potential changes in sounder design or implementation that could yield significant improvements in any of the above (e.g., transmitted power, wave shape, use of multiple frequencies, receiver sensitivity, antenna size and geometry, orbit, addition of 2^{nd} receiver – either boom-mounted or on an adjacent orbiter, etc.)?

2. Massive Bodies of Segregated Ground Ice: In addition to ice that may occur within the frozen saturated zone, variations in depositional history may have resulted in emplacement of massive segregated lenses ranging from ~1-100's of meters thick (e.g. frozen lakes, oceans; Fig. 3).

Primary science questions related to this target:

i. Is there evidence of massive bodies of segregated ground ice, resulting from the ponded dischage of the outflow channels or the presence of an ancient ocean, in the northern plains?
ii. Can such deposits be identified within/beneath large impact basins/craters?
iii. If so, what is the depth/distribution of these ice bodies?

3. Liquid Water*:* Liquid water may be present in the subsurface in a variety of forms and potential distributions. During the summer, at low-latitudes, the temperature of the top few centimeters of the regolith may exceed 273 K for as much as a few hours a day – sufficient to melt near-surface ice or frost and produce transient films of liquid water on mineral grains. The presence of potent freezing-point depressing salts could conceivably extend the duration and extent of melting, particularly at equatorial latitudes. Near-surface liquid water might also occur in association with local geothermal anomalies.

Within the lowermost km of the cryosphere, thin films of super-cooled liquid water are expected to occur on the surfaces of mineral grains as the crustal temperature reaches values that are within 20 K of the freezing point. Beneath the cryosphere, the distribution of liquid water may be quite complex. If the subpermafrost inventory of liquid water is large, the vast bulk of it is expected to saturate the lowermost porous regions of the crust, forming a groundwater table in effective hydrostatic equilibrium. For this reason, in regions of low surface elevation, the base of the cryosphere and groundwater may be in intimate contact (e.g., Fig. 2); while, in regions of higher elevation, the base of the cryosphere and water table may be separated by an unsaturated zone of many kilometers. Capillarity, and the effects of low-temperature hydrothermal convection, are likely to contributed to a gradational transition in saturation state that precludes identification of a clear interface between saturated and unsaturated conditions. These process are also likely to produce complicated stratigraphic variations in saturation state between the base of the cryosphere and water table, including the development of perched aquifers.

Primary science questions related to this target:

i. Is there a water table on Mars and, if so, what is its three dimensional configuration?
ii. Do hydrothermal or other near-surface reservoirs of liquid water/brine exist? If so, what is their spatial distribution?
iii. What is the 3D configuration of the surface defining the base of the cryosphere? Where is

this surface most accessible to a possible future drilling mission?

iv. What is the degree of water saturation of the rocks below the base of the cryosphere?

Related technical issues:

What is the smallest volume and minimum depth that liquid water/brine could be detected by an orbital sounder?

Does the likely presence of continuous, thin-films of super-cooled liquid water on mineral grain surfaces at the base of the cryosphere preclude the identification (and mapping) of liquid water at greater depths?

4. Polar Layered Deposits:

Primary science questions related to this target:

i. What is the thickness, extent and continuity of the layers within the polar deposits?

ii. Is there geophysical evidence of prior variations in vertical and areal extent?

iii. Is there evidence of flow in the internal structure or other characteristic of the caps?

iv. Is there evidence of past or present basal melting or basal lakes?

v. Are there peripheral ice deposits that may have been associated with local discharges of subpolar or subpermafrost groundwater?

5. Gas Hydrates and Liquid CO_2:

Primary science questions related to this target:

i. What is the 3-dimensonal distribution/concentration of gas hydrates and liquid CO_2 in the crust?

Related technical issues:

Do gas hydrates and liquid CO_2 have characteristic geophysical signatures that are detectable by an orbital sounder?

If so, to what level of confidence and highest resolution (e.g., maximum/minimum: concentration, volume, depth, contrast)?

6. Local and Regional Variations in Crustal Lithology and Structure:

Primary science questions related to this target:

i. What is the 3-dimensional tectonic, volcanic and sedimentary structure of the crust?

ii. How does the porosity of the crust vary geographically and at depth?

Related technical issues:

Are layering and tectonic structures (e.g., faults) detectable by an orbital sounder and, if so, at what resolution? Specific examples: Valles Marineris, Medussae Fossae formation, polar layered deposits, etc.

7. Compositional and Electromagnetic Properties of the Crust:

<u>*Primary science questions related to this target:*</u>

i. What is the vertical distribution and composition of brines, iron oxides, carbonates, etc. within the upper crust?

<u>*Related technical issues:*</u>

What are the sensible electromagnetic properties that can be exploited to differentiate these strata?

8. General Technical Questions:

i. Are there potential changes in sounder design or implementation relative to MARSIS that could yield significant improvements in any of the above (e.g., transmitted power, wave shape, use of multiple frequencies, receiver sensitivity, antenna size and geometry, orbit, addition of 2nd receiver – either boom-mounted or on an adjacent orbiter, etc.)?

ii. Can an orbital radar sounder be used to identify targets with sufficient confidence and resolution to access them by drilling?

iii. Does an orbital sounder provide any additional capabilities to characterize or assess the safety of potential landing sites?

E. Ambiguities and Potential Complications in the Interpretation of Geophysical Data

Terrestrial experience has demonstrated that the accurate interpretation of geophysical data is likely to require the application of multiple geophysical techniques (Stoker, 1998). The same lesson is no less true for Mars. In this context, radar sounder data can be relied upon to indicate areas of potential interest, and should effectively inform plans for subsequent surface investigations designed to "follow the water." However, it would not be realistic to view radar sounding as a self-sufficient means of sub-surface water exploration.

A potential complication for the detection of groundwater by orbital or surface radar is the likely presence of super-cooled water within the lowermost kilometer of the cryosphere. Thin films of liquid water are known to persist on mineral surfaces down to very low temperatures (~250 K) particularly in the presence of freezing-point depressing salts. This means that near the base of the cryosphere, where crustal temperatures increase to within ~20 K of the freezing point, an electrically conductive and seismically dispersive region may exist that could pose a significant problem for geophysical efforts to determine the presence and depth of a regional or global groundwater table.

4. Mars Orbiting Radar Sounder Design Issues

There will have been no experience with substantial subsurface depth sounding by radar from orbit until MARSIS begins its mission. Radar sounding from orbit presents many challenges, especially under the circumstances expected at Mars. For example, penetration of the Martian surface to 1 km or more requires low frequency (very long wave) radiation, yet ionospheric dispersion is more severe for low frequencies than for high, and resolution (both vertically and horizontally) is bounded below as a function of wavelength. Penetration also requires sufficient per-pulse energy to excite sensible signals from layers at depth, yet those same signals generate sidelobes and other self-noise that can mask the desired returns. This section reviews the principal issues, outlines the MARSIS radar sounder on the ’03 Mars Express, and elaborates on selected design constraints and extensions open to the ’05 MRO opportunity.

A. Dispersion

The Martian ionosphere poses a major limitation on low-frequency wide-bandwidth radar observations of the surface and subsurface. At these frequencies, frequency-dependent propagation delays (dispersion) will degrade the signal, and compound the task of recovering depth penetration profiles. The ionospheric phase delay at frequency f is proportional to

$$[1 - (f_p/f)^2]^{1/2}$$

where f_p is the plasma frequency (Evans and Hagfors, 1968). Clearly, different frequencies suffer different delays, an effect whose severity increases with relative bandwidth, and with proximity of the radar’s band to the plasma frequency. These perturbations vary both temporally and spatially over the planet. The resulting signal distortion can be sufficient to destroy coherent signal processing unless adequately compensated. The plasma cutoff frequency of the Martian ionosphere has been measured to be about 3.0 MHz during daylight illumination, and is expected to be well below 1 MHz at night.

B. Range (Depth) Sidelobes

Traditional ground-penetrating sounders are radars that operate on (or close to) the target surface to measure the ranges of a sequence of subsurface layers stacked in depth. Sounding radars usually use simple short pulses because these have been proven to have minimal sidelobes (Daniels, 1999). Sidelobes can be devastating for sounding radars, primarily because the desired signals come from depths from which they suffer attenuation, and thus appear at a distinct disadvantage as they compete with energy in the tails of stronger and less attenuated reflections, usually from the surface. The trade-offs between pulse modulation, signal attenuation with depth, and sidelobe levels are the most challenging aspects of sounding radar design.

Radar sounding from a relatively high altitude instrument requires that the pulses convey more energy than is possible for very short pulses. Hence, the design of orbital radar sounders to date has been heavily influenced by ocean-sensing radar altimetry. In these well-known instruments, long linear fm pulses have been the norm for decades (Raney, 1999). One advantage of a long modulated pulse is that its large time-bandwidth product (TBP) can be exploited to render very nice range (height) resolution while at the same time preserving relatively large per-pulse energy. Compression of pulses having large time-bandwidth products requires that the pulse phase modulation must be matched with a precision comparable to 1/TBP. In the event that such precision is not achieved, the range sidelobes in the compressed pulse will increase, and as the mismatch increases the range resolution will be degraded. Sidelobes are not of major concern for an altimeter because the range depth of the scene is very small. In contrast, sidelobes can be the dominant limiting factor for a sounding radar because the equivalent range span of the sidelobes often overlaps the domain from which depth signals are desired. In general, range sidelobe support for large TBP signals is equal to the duration of the original modulated pulse length. A 250-microsecond pulse length, for example, corresponds to about 25 km in depth of the Martian surface in which sidelobes will exist that are generated by reflections from the surface. The principal sidelobe neighborhood shrinks to about 3 km in depth for a 30-microsecond pulse.

The range sidelobe and resolution problem is compounded at Mars due to ionospheric dispersion. Accurate coherent pulse compression requires detailed knowledge of the modulation of the returning signals, but their (two-way) propagation through the ionosphere distorts their phase structure. Thus, the end-to-end pulse modulation must be estimated, as it cannot be known *a priori*. One approach is to use the strong quasi-specular surface return as a reference to map the dispersion properties. Indeed, the (conjugate) surface return could be used as the pulse compression reference signal. This approach is well suited for Mars, for which much of the surface appears to be smooth (quasi-specular) at the long wavelengths to be used for subsurface sounding. Reported results using this technique based on simulations are promising (Safaeinili and Jordan, 2000). Although challenging, it should be possible to match the dispersion characteristic of the ionosphere across signal spectra to a tolerance that is comparable to 1/TBP.

In a situation in which very high dynamic range signals (>60 dB) may be in competition, range sidelobe suppression is a major concern. Sidelobes become important if their power is comparable to or greater than a desired signal that they could overwhelm. Thus, if such a signal is to be observed by a pulse-compression technique, residual sidelobes due to reflections from the Martian surface and that overlap the desired signals from depth must be suppressed by more than the signal level, plus the desired SNR margin for reliable detection. This may be difficult to accomplish. For example, in a recent exercise that was designed to test just this question, it was concluded that long linear fm pulse techniques tend to mask weaker reflections from internal features (Moussessian et al., 2000).

C. Operation Frequency Choice

The radar sounder on MRO should look for a solution that may do a better job responding to the post-Mars Express requirements. If the objective is higher resolution penetration into the first km, then ~15 MHz should suffice, in contrast to the upper frequency of ~5 MHz of MARSIS. Even higher frequencies could be given serious consideration. To first order, under the conditions expected at Mars, depth penetration is proportional to wavelength, hence inversely proportional to frequency.

Given that the MARSIS design has low enough frequency to probe 5-6 km, as designed, then the same performance should be achieved at 1/5 the depth using a frequency 5 times higher. MARSIS Claims penetration of 5-7 km under "nominal" conditions for the lowest band which is centered at 1.8 MHz. The corresponding penetration depth for 15 MHz would then be 600-800 m.

There are several non-trivial benefits to the higher frequency. These benefits include:

(1) Dispersion. The dispersion problem is much less severe, as can be seen from the phase delay equation cited in above. Dispersion sensitivity is proportional to the square of the ratio of the plasma frequency to the radar frequency. Hence, an increase in frequency by a factor of three decreases the impact of dispersion by nearly an order of magnitude. This is particularly significant if higher bandwidth/finer resolution is to be achieved.

(2) Percent bandwidth. A given signal bandwidth at a higher carrier frequency implies a smaller percent bandwidth. Although this may appear to be obvious, implementation challenges should be relaxed. Likewise, the effect of dispersion is proportional to the square of the percent bandwidth, to first order. Hence, smaller percent bandwidths imply less sensitivity to dispersion effects.

(3) Antenna. The length of the antennas can be reduced by a factor commensurate with the increase in frequency. Again, this may be significant for spacecraft design and dynamics. This advantage will be limited, of course, by the lowest frequency required, rather than the upper bound.

(4) Cross-track clutter suppression. With shorter antennas, the design may admit consideration of cross-track interferometric means to suppress off-nadir clutter.

(5) Fresnel diameter. The Fresnel diameter shrinks as the square root of (1/frequency), so a frequency higher by, say, a factor of four would cut the Fresnel zone in half. At 20 MHz, for example, the Fresnel diameter would be about 2.5 km, which is getting closer to the more aggressive along-track resolutions in demand for certain applications.

(6) Doppler enhancements. Doppler frequency increases in proportion to center frequency. At the higher frequencies there is more (potentially useful) Doppler structure in a group of signals, which could be exploited to improve along-track resolution and sounding performance under favorable circumstances. Again, one can tailor the processing strategy to the nature of the observed reflections, since the data will be processed on the ground.

(7) Resolution. Whereas resolution in general is inversely proportional to bandwidth, that theoretical limit is progressively more difficult to meet for large percent bandwidth signals. Stated alternatively, low frequencies cannot readily support resolutions that approach the wavelength of the radar.

On the other hand, there also would be disadvantages to a higher frequency. The principal issues include:

(1) Clutter. Competing clutter signals arise primarily from scatterers that lie off-nadir and to the side of the sounder's surface track, and appear at the same radar range as the desired signals from depth. Surface slopes having nadir-facing gradients of only a few degrees or less will compete with signals from the top internal kilometer or less. Along-track clutter will be suppressed by Doppler filtering. In general, off-nadir scattering is due primarily to features whose facets face the radar and have length scales comparable to the illuminating wavelength. At 15 MHz, which could be considered as an upper frequency bound, the corresponding free-space wavelength would be 20 meters, in contrast to the longer 60-

meter wavelength of 5 MHz radiation. As the wavelength is decreased, the population of qualifying scatterers may be expected to increase. Furthermore, reflecting facets that tend to face the radar will give rise to larger backscatter. Smaller facets tend to have larger mean slopes. In short, higher frequency implies increased clutter.

(2) Ionospheric Correction. Additional clutter will impact ionospheric correction since the surface return can no longer be considered as the point spread function for the ionosphere.

(3) Signal loss due to surface roughness. At larger wavelength, the surface of Mars behaves like a well-polished mirror; as the wavelength is shortened, this condition will not hold and as a result both the surface and subsurface reflections will degrade.

(4) For shorter wavelengths, the spacecraft real-time orbit knowledge requirements becomes more stringent. The orbit knowledge accuracy is critical to on-board data reduction.

(5) Adjacent orbit processing. Shorter wavelength also reduces maximum orbit separation. This could eliminate the possibility of adjacent orbit processing which is needed for clutter reduction.

(6) Penetration depth. The subsurface radio attenuation characteristic is not known. As a result, a high-frequency radar will be at risk of not meeting its maximum penetration depth science requirement. This is particularly of concern since it will not be able to benefit from the MARSIS science data.

(7) Synergy with MARSIS. A lack of frequency overlap with MARSIS will limit cross-analysis with MARSIS data.

(8) Radar penetration into lossy media in general is proportional to wavelength, all else equal. However, this fact can be turned to advantage. If the sounder's objective is the top kilometer rather than five kilometers, a radar whose frequency is, say, three times higher than it was for MARSIS actually represents a more conservative and robust design approach.

D. Galactic Noise

The galactic noise plays an important role in medium and high frequency regime. This noise source is significantly stronger than the electronic thermal noise. As a result, the galactic noise will be the limiting factor on the sensitivity of the radar. The galactic noise will decrease as the operation frequency increases.

E. Electromagnetic Compatibility

Electromagnetic compatibility between radar and the spacecraft and other science instrument is an important issue that needs adequate attention. Radars by definition generate large E-fields (impact of radar on the spacecraft) while requiring an interference-free environment for reception of weak subsurface echoes (impact of the spacecraft on the radar). Both of these issues need to be addressed and incorporated in the design of the spacecraft.

F. Potentials for Mission Enrichment

The self-noise generated from surface clutter in competition with subsurface signals may arise as a limiting factor. This effect is most likely to be significant for shallow sounding. Further, many areas of interest may lie in relatively rough terrain, such as near crater rims and surface ridges. In such circumstances, the ability of any radar sounder to suppress these unwanted returns will be modest at best if the data analysis is restricted only to data collected along a single pass of the satellite.

The combination of the nominal MRO ’05 orbit properties and the very long wavelengths required by the radar sounder leads to rich potential means of enhanced performance. The candidate strategies all rely on the availability of data from adjacent orbits. Such data can be processed either incoherently, or coherently. Techniques for coherent interferometry have been applied very successfully to large percent bandwidth long-wave radar data (Ulander, 1998). This potential would be best met by a near-repeat orbit plan, rather than the nominal exact-repeat pattern now contemplated in the ’05 mission planning.

As a logical extension, data from a sequence of several adjacent orbits could be coherently processed to accumulate an effective 2-dimensional aperture. If correctly organized and constrained, such a “creeping orbit” strategy could be sufficient to support a quasi-holographic downward-looking depth imager. The first-order benefits of this strategy would be unambiguously to suppress cross-track clutter, and to increase cross-track resolution. Performance would depend on the frequency selected, and on orbit control and knowledge.

5. MARSIS and The MRO Sounder

In this section, first a review of MARSIS will be presented in which a brief overview of MARSIS design will be discussed. Next, the proposed sounder for the MRO will be presented and the potential improvements over MARSIS will be outlined.

The following comment was prepared as an introduction to a comparison of MARSIS and MRO. The "requirement" that the antenna be aligned across-track for MARSIS is not true for MRO. MARSIS has a much tighter spec on the cross-track antenna pattern so that they could use data from the monopole to (partially) cancel clutter from the side. This is not needed on MRO, as there is to be no monopole. IF the antenna were to be aligned cross-track, the 2005 Project had loaded the s/c mass (and cost and risk) budget with more than approximately 16 kg to cover a second degree of freedom in the solar panels. However, this is not needed. The "optimum" configuration would see the antenna long axis orthogonal to the solar panels. In turn, the s/c always should be oriented such that the solar panels fully faced the sun. In addition to simplifying the s/c, there is an added science benefit. This geometry would result in crossing orbits (ascending and descending) to have the same polarization of the surface/subsurface relative to local features. In response to any lineations, such alignment would be essential for both clutter cancellation through cross-over analysis, and for generating maximal coherence for orbit-orbit interferometry.

A. MARSIS at Mars

The main objective of the MARSIS sounder on Mars Express is to image subsurface features, especially area-extensive layers, to a depth of 5 km with depth resolution of about 100m in situ. (Picardi et al., 2000). MARSIS performance will be constrained by its orbit, and by certain features of its design. The Mars Express orbit is highly inclined (~86 degrees) and elliptical, having periapsis height above the Martian surface of ~250 km, apoapsis height of ~10142 km, and a period of ~6.75 hours, from which about 25 minutes are available each orbit for sounder observations. The radar when in the subsurface sounding mode below 800 km will utilize a 30-microsecond or a 250-microsecond long linear fm pulse sweeping a 1-MHz bandwidth, centered at 1.8 MHz, 3 MHz, 4 MHz, or 5 MHz. One or two of these frequencies will be used at a time, depending on the operating mode. Rejection of clutter from scatterers spread in Doppler will be accomplished by Doppler filtering. Scatterers spread across-track, and hence possibly in range/Doppler competition with the desired signals from depth, will be partially suppressed by clutter cancellation techniques derived from a second asymmetric antenna pattern. The longer pulse length of 250 microseconds is to be compressed to the equivalent of 1 microsecond after processing, for an effective time-bandwidth product (TBP) of 250 (Picardi et al., 2000).

Marsis's main on-board processing task is reducing the data redundancy and increasing signal SNR. This is achieved by a presumming operation which reduces the data rate by a factor of ~200. In order to preserve the doppler information, many of MARSIS operation modes carry out the presumming operation over 3 or 5 separate doppler channels. The presummed data are then transmitted to the ground for ionospheric correction and range compression. In addition to the normal processed data modes, MARSIS has a raw data mode where raw data can be downlinked for selected spots.

MARSIS uses two principal strategies to help overcome the range sidelobe problem: the option of a shorter pulse (30 µs), and ground-based (and hence more readily optimized) range-compression. It is expected that the MARSIS processed signals will have a dynamic range that is less than 50 dB. This implies that the sidelobe suppression requirement is -60 dB relative to the peak at 80 µs delay (~5 km depth), under the conditions that the signals from the surface and from depth have the same reflectivity prior to attenuation, and that a 10 dB signal-to-noise ratio (SNR) is desired for reliable detection of the deeper layer. The main uncertainty that can degrade signal compression accuracy, and hence cause increased sidelobe levels, is ionospheric dispersion. This ionospheric dispersion must be accurately estimated if an optimized compression algorithm is to be effective. Such optimization is more readily achieved if the primary processing is implemented adaptively on the ground rather than in autonomous on-board algorithms. A number of factors that were considered in delaying the range compression to the ground-processing stage are given below.

Disadvantages to on-board dedispersion:

1. Due to the real-time nature of the on-board processing, the estimation of the ionosphere can not be accurate enough to suppress the sidelobes effectively.
2. Any on-board correction would be unknown unless the ionosphere dedispersion information is downlinked at the cost of reducing the science data rate by a factor of 2.

Advantages to range compression during ground processing:

1. Higher quality range-compression at no cost to the science data rate.
2. Ionospheric information is contained in the surface return which would have been discarded during on-board processing (a secondary science value at no cost).

More details on the MARSIS design may be found in the Appendices 2 and 3.

B. The Radar Sounder on MRO

The nominal orbit being considered for the ’05 orbiter is similar in latitudinal coverage to that of Mars Express, having an inclination of 93 degrees. The similarity ends there, however. The ’05 baseline orbit is to be circular at 400 km height above the mean surface, and sun-synchronous with a period of about 118 minutes. These facts have profound beneficial impact on the design of a new generation of radar sounder. The lower mean altitude of MRO means that the radar’s transmitted energy will be stronger at the surface by as much as four times that available from the Mars Express orbit, which should translate into better depth penetration and subsurface imaging. In contrast to MARSIS, the ’05 sounder has the freedom to concentrate its observations on the dark side of the planet (spacecraft resources permitting) which will allow lower radar frequencies, which in turn will maximize surface penetration. Increased distance between the radar’s mean frequency and the plasma cutoff frequency will help to minimize ionospheric signal perturbations. Because of the reduced spacecraft velocity of MRO over the surface, greater integration time will be available, which can be exploited to reduce end-to-end data rate, and to increase the quality of the derived depth profiles. Furthermore, the ’05 orbit period is about one-quarter that of MARSIS. Thus, a sounder on MRO will be able to collect subsurface data approximately ten times more rapidly than

MARSIS. Not all of this potential can be realized, however. The average science data rate from MRO will be only about three times larger than that of Mars Express.

Several design concepts have been identified for a second-generation radar sounder for MRO that promise to provide performance enhancements in comparison to MARSIS. These concepts are explored in more detail in section 5.

C. A Radar Sounder for MRO (ASI)

Given the nominal characteristics of the 2005 mission, one can envisage an instrument to support investigations that complement the results of MARSIS. Note that MARSIS was designed before MGS data were obtained and interpreted. Likewise, its scientific requirements were established on the basis of knowledge of Mars at that time (Picardi et al., 2000). The then dominant constraint was that the depth of the cryosphere bottom was large, ranging from 2.3 km at the equator to 6.5 km at the poles (see for example *Water on Mars*, by M. Carr -Chapter 2 and discussion therein). The models also suggested that the hydrosphere could be at even greater depth, depending on choice of model key parameters, such as layer thermal conductivity and thermal inertia, porosity and geothermal gradients. On the basis of that knowledge, the MARSIS radar was designed with the primary objective to map the distribution of water, both liquid and solid, in the upper portions of the crust of Mars, assuming that the nominal depth of the melting isotherm ranges in the range 0 m - 5000 m (Picardi et al., 1999). The results gathered by MARSIS should provide unprecedented knowledge of a planet at broad regional level, and will be extremely important for the reconnaissance of large and well-defined ice and water reservoirs.

The new knowledge developed thanks to MGS indicates that sedimentary processes are more complex than anticipated before, and that they are possibly related to the water history on Mars. Moreover some of the MOC images seem to indicate the presence of shallow ice/water reservoirs. Given the comparative maturity at this time of our insight into the likely Martian subsurface structure, one can surmise certain limitations in the MARSIS design. These may become evident particularly when sounding regions where the interface between desiccated regolith and permafrost and/or permafrost and aquifers is not sharply defined, but rather shows a gradual transition. Another potential limitation of MARSIS is related to the difference between horizontal and vertical resolutions. For example, at 250 km (the Mars Express periapsis altitude), the horizontal resolution will be about 5 km x 10 km, while the vertical *in situ* resolution is designed to be 50 m - 100 m, depending on material dielectric properties. These resolutions are relatively coarse, which can make the correlation between the surface geomorphology and the radar reconstructed stratigraphy quite complex.

Our understanding of the Martian near-subsurface would be improved with more detailed information of the upper several hundred meters of the Martian crust than MARSIS is able to provide. Better differentiation of the physical features of the crust would be achieved through deconvolution, and with finer resolution. Post-detection deconvolution would help to suppress extraneous surface scattering and certain aspects of signal self-noise. Correctly implemented, this would improve estimates of the dielectric constants derived from the sounding profiles, and thus provide better characterization of the physical nature of deeper subsurface interfaces. An instrument able to penetrate a few hundreds of meters below the surface with a finer horizontal resolution and a vertical resolution (on the order of 10 m - 20 m) would help to achieve these objectives. Moreover such an instrument should provide a unique insight into the Martian stratigraphy at scales comparable to those of optical images, thus offering a tremendous improvement in the understanding of sedimentary processes and recent geologic activity.

For the previous reasons a second generation radar sounder for the ’05 MRO mission might be described by the following high-level parameters:

Penetration Depth:	300 m –1000 m
Vertical Resolution	10-20 m
Horizontal resolution	300 m-1000 m

These numbers suggest that more emphasis should be placed on the higher frequency bands than are available on MARSIS, and that a wider bandwidth signal must be used.

D. Marrying Objectives and Constraints

Prior to introducing alternative concepts for subsurface imaging at Mars, it is helpful to take note of certain considerations that are likely to dominate the measurement environment. First, the relatively long free-space wavelengths (60 m to 300 m) required to achieve useful penetration imply that the principal mode of reflection will be coherent from nominally horizontal quasi-smooth layers, either at the surface or below. In this context, “quasi-smooth” means that the surface has mean vertical variations of less than about one-tenth of the illuminating wavelength (in situ). The reflected power from such surfaces goes only as $1/R^2$ (where R is the total effective range from the radar to the surface), as opposed to $1/R^3$ or $1/R^4$ for quasi-rough or isolated scatterers, respectively. Thus, the smoother layers will dominate. This implies that the spatial resolution that any radar might achieve will be limited below (for such surfaces) by their effective area, for which the Fresnel diameter is a reasonable approximation. (Fresnel diameter is proportional to the square root of wavelength.) To within a factor of two or so, the Fresnel diameters seen from a radar at 400 km altitude vary from about 5 km (at 5 MHz) to about 11 km (at 1 MHz). Attempts to achieve along-track spatial resolution below these numbers in general will be fruitless for such features. Therefore, a reasonable radar design will take advantage of all means of signal averaging and integration subject to an effective data posting upper bound of about 5 km along track, at the surface. This characteristic makes sense from an applications viewpoint as well, since larger (potential) bodies of ice or water layers should have more significance than smaller ones.

Second, although it makes sense for the sounder design to be influenced primarily by extensive quasi-smooth surface features, the instrument also should support higher-resolution imaging along track. If the sounder is operated coherently, then there will be a trade-off between coherent and incoherent pulse-to-pulse integration. The principal strategies and benefits of these options have been demonstrated using radar sounder data from the Greenland ice sheet (Raney, Gotwols, and Jensen, 2000). The trick is to strike a balance between initial pulse-to-pulse coherent integration (pre-summing), and parallel Doppler processing with partially coherent integration (Raney, 1998). Parallel Doppler processing is less effective for quasi-smooth layers than for more spatially differentiated scatterers.

Third, there is an inherent trade-off between penetration and depth resolution. Unless an interferometric measurement is undertaken, wavelength establishes the effective lower bound on depth resolution. Penetration is favored by longer wavelength (lower frequency), whereas the latter is favored by shorter wavelength (higher frequency). For reference, note that the shortest wavelength used by MARSIS is about 60 m in free space, or on the order of 24 m in situ. Now it is not reasonable to assume that layers of interest will always lie deeper on the dark side of the planet, where they would be relatively open to long-wave probing. Likewise, it is not reasonable that closely-nested layers nearer to the surface should lie always on the solar side of the planet. One strategy would be to probe the surface with a signal that can elicit useful data either from depth or with finer depth resolution. This objective can be met with a signal comprising a full span of frequencies (say 1.3 MHz – 5 MHz), or by designing a coverage strategy that would emphasize either depth or resolution, depending on solar illumination.

Due to the ionospheric dispersion, high quality profiles require intensive and adaptive signal processing. This is best accomplished on the ground, subject to the constraints of science down-link data rate. On-board signal processing should be exploited to reduce the data rate and volume, but at no loss of science value. If computational resources permit, selected depth profiles should be generated on-board. These should be included in the data telemetry, and would serve as near-real-time confirmation of radar sounder mode and operation. The above is essentially the MARSIS approach.

6. Second Generation Radar Sounder Design Options

There are several options available that would enhance a radar sounder's capabilities at Mars. These include variations on the MARSIS design (Section A), alternative waveform designs such as the Stepped Frequency Modulation (Section B), a Ricker Wavelet Modulation (Section C), or an Inverse Dispersion Waveform (Section D), and a High Frequency Surface Penetration approach (Section E). An outline of a conceptual approach from the IAS (Italy) is alsosummarized (Section F). In all cases, the design should make full use of available power, both in the instrument design and in the signal processing algorithms. The main message of this section is to illustrate concepts through which a second generation radar sounder can be implemented that would provide sounding data from the '05 opportunity that would (1) be responsive to the MRO science requirements, and (2) provide significant science data beyond those expected from MARSIS.

A. MARSIS Heritage Sounder

This option builds on MARSIS heritage but makes appropriate modifications to improve shallow sounding performance. One requirement for shallow sounding is finer vertical resolution, which requires a larger bandwidth. Although MARSIS spans a bandwidth of 4 MHz, those bands are not continuous nor are they easily combined to achieve larger effective bandwidth. One could design a radar with multiple bands similar to MARSIS, but which overlap, and provide for near-simultaneous operation. For example, there could be a total of four bands each with a 1.3 MHz bandwidth, covering from the lowest frequency at 1.4 MHz to 6 MHz with band overlaps of 0.2 MHz. Band overlap would help to maintain cross-band calibration and frequency continuity.

Two distinct operation modes could be supported: shallow sounding mode (surface to 1 km), and deep sounding mode (surface to 5 km). This radar would operate with full bandwidth at the shallow sounding mode and at reduced bandwidth at the deep sounding mode.

A variety of pulse patterns can be considered. In one pulsing scheme, a single fixed PRF (pulse repetition frequency) is assumed. However, the pulsing pattern within the PRI (pulse repetition interval) can be changed depending whether the operation is in the deep or the shallow mode. In the deep sounding mode, within a given PRI two longer chirps are transmitted with an effective bandwidth equivalent to one or two bands depending whether pulse 1 and 2 are from the same band or different bands. In the shallow sounding mode, there are four shorter chirps covering all or a subset of bands. This mode will have the highest possible system bandwidth.

The PRF is selected such that there is only one set of pulses in transit at a given time. This will mean this design will have a PRF of few hundred Hz (200-300) depending on the orbit altitude. In order to improve signal-to-noise ratio (SNR), the total transmitted energy is maximized by increasing the chirp length to the maximum allowed.

Based on the lowest band frequency selection for this example, an optimum antenna length is about 60 m . The antenna length may be reduced by increasing the radar operating frequency. It is also possible to reduce the antenna length at the expense of the antenna radiation efficiency at the lowest frequency band. Another problem facing the proposed sounder is a relatively large bandwidth to center-frequency ratio which is in the range of 30% to 100%. Achieving a uniform high radiation efficiency across the band is a difficult engineering challenge. One means of partially avoiding this problem is to have four dipoles, one for each of the four center frequencies. Such an antenna could be implemented with four wires, all of which could be supported in one radio-transparent tube.

A more detailed discussion of this design is presented in Appendix 4.

B. Stepped Frequency Modulation

It has been recognized for many years in the field of ground-penetrating radar (GPR) that the preferred approaches avoid sidelobe generation. If energy budgets allow, a simple short pulse has been proven to be most effective, the so-called brute strength method. An alternative is to transmit the spectrum that corresponds to a short pulse. One means of doing this that has proven to be very successful in the field of GPR is the so-called stepped frequency technique (Izuka et al., 1984).

The stepped frequency technique would appear to be well-suited to the constraints to be encountered at Mars. The concept may be visualized as transmitting a discrete Fourier transform of a short pulse, which appears as a family of N continuous wave (quasi-cw) burst transmissions, each at a different frequency. In this sense, the stepped-frequency approach is the dual in transform space of the short pulse. Design principles for this class of radar are well known (Wehner, 1995). The general scheme is to transmit a sequence of quasi-cw bursts that are uniformly separated in frequency. In a dispersive environment, it makes sense to sweep from higher to lower frequencies so that the effects of dispersion would increase the time separation between cw samples, rather than to crowd or overlap them in time. Resolution is limited by the inverse of the bandwidth spanned by the transmitted frequencies, and the unambiguously imaged range interval (scaled by the in situ propagation velocity) is determined by the inverse of the difference between transmitted frequencies. In a step-frequency radar, the frequency step (δf) determines the unambiguous range, and the product N δf sets the total signal bandwidth, hence establishing the range resolution. In effect, the stepped frequency approach is a discrete version of linear fm encoding. The stepped-frequency approach accommodates alternative Doppler processing strategies very readily, and can be configured to support along-track resolutions from 5 km to less than 1 km, as the surface situations warrant.

As with any large TBP approach, imperfections in matched signal coherence can lead to increased side-lobes. However, these side-lobes can be controlled more effectively in a stepped-frequency system than those of a long linear fm modulation technique because the dispersion estimation algorithm can rely on a discrete set of known quasi-cw tones rather than a continuous spectrum. The effects of dispersion in either the antenna or the ionosphere can be estimated by measurements derived from the first-surface return, similar to the scheme to be used for MARSIS data. In the stepped-frequency case the relative propagation delay at each discrete frequency can be observed independently, which should support more accurate results than are possible from a chirp signal. The objective is to shift the time-reference for each of the cw constituents such that their relative coherence (phase registration) is restored.

C. Ricker Wavelet Modulation

As has been appreciated for many years, radar sounding is far better served by unity time-bandwidth product short pulse modulations that can be detected in simple time sequence, than by longer coded pulses that require correlation techniques for their transformation into time-resolved waveforms (Daniels, 1999). A short pulse approach is an obvious design that might be considered for a Martian radar sounder. However, there are two disadvantages to a straight-forward approach. First, and most obvious, much less energy can be packed into a short pulse than a long one. For example, a 1-microsecond pulse of the same peak power as a 30 microsecond pulse would be 30 times less energetic, which would imply about a 14 dB disadvantage in detection SNR. However, if the peak power of the shorter pulse could be increased, the trade-off would be less severe. In the event, therefor, that there were excess peak power available, and that the dominant performance constraint was self-clutter from sidelobes and the like, then a simple short pulse radar sounder would qualify as a candidate solution.

However, at Mars there is a second and more substantive consideration: the effects of dispersion. If a short pulse were radiated by the radar, after two-way propagation its constituent frequencies would be spread out, effectively broadening the pulse. For example, more than 30 microseconds of differential delay may occur across the bandwidth of a moderate-resolution pulse (Safaeinili and Jordan, 2000). Thus, a 1-microsecond transmitted pulse after perfect flat-surface reflection would be transformed into a ~30-microsecond received pulse, which would defeat the purpose of the short pulse paradigm.

The Ricker wavelet, which is a special shape of the short pulse paradigm, has been shown to have favorably low sidelobes, especially in application to radar sounding into a lossy medium (Daniels, 1999). However, the ionospheric dispersion would prevent a Ricker wavelet from being used, just like any other short pulse scheme. There is an alternative, however. Combine the step-frequency approach and the Ricker wavelet approach. In effect, the radar's signal would consist of a sequence of the weighted discrete frequency components of the spectrum of a Ricker wavelet.

D. Inverse Dispersion Modulation

There is a special case of signal modulation that would take advantage of the dispersive characteristics of the ionosphere. The pulse frequency modulation could be adapted to the dispersion characteristics observed in real time. There are two aspects to this concept: (1) dispersion estimation, and (2) signal modulation. Dispersion can be estimated from the spectral distribution imposed upon a simple short pulse transmission. The radar would transmit a sequence of short probing pulses, followed by a sequence of coded pulses whose modulation would be adapted to the prevailing dispersive environment. The technique requires sufficient on-board processing power to implement a spectral analysis of the received probing pulses, whose output would control the modulation to be applied to the signal generator for the depth sounding pulses. The short probing pulses would give rise to surface reflections that would be sufficient to estimate the two-way propagation dispersion properties. Spectral analysis would consist essentially of a Fourier transform of the envelope of the averaged surface returns from the short pulses.

Once the dispersion was characterized, the radar signal generator would then use the frequency characteristic to create the desired signal modulation. At this point there are two options. One obvious choice is to generate a signal modulation that is the inverse of the ionospheric dispersion. Thus, the received pulses would be compressed naturally following their two-way propagation. This has the disadvantage of requiring that the receiver have a very large dynamic range. There also may remain sidelobe interference problems, since the pulse as it probes the surface will in general have time-bandwidth product greater than unity. Although an obvious possibility, this method is not necessarily the best available.

The alternative modulation strategy would be to program the pulse modulation to match the inverse of one-way propagation. Thus, each probing pulse in effect goes through a matched pulse compression filter as it propagates to the surface. Assuming reciprocity, the one-way dispersion characteristic is in effect a frequency scaling (by one half) of the two-way dispersion. As a result of the one-way inverse dispersion modulation, the surface would be illuminated by true short pulses. The signals from the surface and from depth returned to the radar would be dispersed by the return path through the ionosphere. The principal advantages of this approach are that the system dynamic range requirements would be less than for the two-way inverse dispersion modulation, and that the sidelobe problem should be categorically minimized relative to all other options. One disadvantage of this approach may be the reduction in the science data rate by a factor of two since it is necessary to down-link the variable transmitted chirp along with the radar data for each frame.

7. Science Objectives *versus* Radar Sounders

As summarized in Table 1, some of the 22 specific itemized subsurface science objectives described above in Section 3D will be met by MARSIS, but others will not. Many of those that may not be well met by MARSIS would be better served by a suitable Second Generation instrument. The discussion that follows elaborates on the specific items enumerated in the table.

Table 1. Summary of science questions related to radar sounding.

		Capability to Address Science Questions			
		MARSIS		2nd Gen. Radar	
Question #	Link to MEPAG Hierarchy	Shallow (<1000 m)	Deep (>1000 m)	Shallow (<1000 m)	Deep (>1000 m)
Saturated/Unsaturated Frozen Ground					
D1-I	IA-1, IIA-1, IIIA-1, IVA-3	3	2	1	1
D1-ii	IA-1, IIA-1, IIIA-1, IVA-3	3	2	1	1
D1-iii	IA-1, IIA-1, IIIA-1, IVA-3	3	2	1	1
D1-iv	IA-1, IIA-1, IIIA-1, IVA-3	3	3	3	3
Massive Bodies of Segregated Ground Ice					
D2-I	IA-1, IIA-1, IIIA-1	2	2	1	2
D2-ii	IA-1, IIA-1, IIIA-1	2	2	1	2
D2-iii	IA-1, IIA-1, IIIA-1	2	2	1	1
Liquid Water					
D3-I	IA-1, IIA-1, IIIA-1, IVA-3	2	1	1	1
D3-ii	IA-1, IIA-1, IIIA-1, IVA-3	2	NA	1	NA
D3-iii	IA-1, IIA-1, IIIA-1, IVA-3	NA	3	NA	2
D3-iv	IA-1, IIA-1, IIIA-1, IVA-3	NA	3	NA	2
Polar Layered Deposits					
D4-I	IIIA-1	3	2	1	2
D4-ii	IIIA-1	3	3	1	3
D4-iii	IIIA-1	3	3	2	3
D4-iv	IIIA-1	2	1	1	1
D4-v	IIIA-1	3	2	1	2
Gas Hydrates and Liquid CO2					
D5-i	IIIA-1	3	2	1	2
Local and Regional Variations in Crustal Lithology and Structure					
D6-i	IIIA-6	2	2	1	2
D6-ii	IIIA-6	2	2	1	2

Ratings scale: 1 = high, 2 = medium, 3 = low

Assumptions in ranking capabilities of MARSIS and 2nd generation sounder to address science questions:

1. *MARSIS performs reasonably close to its design.*
2. *The 2nd generation sounder has the following improvements over MARSIS: high resolution shallow subsurface capability, and better global coverage due to a better orbit.*
3. *The 2nd generation sounder has a deep sounder mode at least as capable as MARSIS.*

For convenience, abbreviations are used in the following comaprisons. These are:
MS=MARSIS shallow, MD=MARSIS deep, 2S=2nd generation shallow, 2D=2nd generation deep.

1. Saturated/Unsaturated Frozen Ground:

i. How does the depth of desiccation vary geographically?

This is assumed to be mostly a shallow phenomenon, so MS is low. Ice and rock are difficult to distinguish, so MD is medium. 2S is high due to shallow location. 2D is high due to better geographic coverage.

ii. How does the saturation state of the crust vary stratigraphically and geographically beneath the shallowest occurrence of ground ice?

Basically the same argument as above, although the question may need to be rephrased ("the shallowest occurrence") to keep the deep capability relevant.

iii. How large is the variability of both of the above at m- to km- size scales?

Same as above, though 2D and 2S get extra points for being higher resolution.

2. Massive Bodies of Segregated Ground Ice

i. Is there evidence of massive bodies of segregated ground ice, resulting from the ponded discharge of the outflow channels or the presence of an ancient ocean, in the northern plains?

The only 1 on this one is for the 2S, if the bodies are thin and near the surface. Others are 2 because ice vs. rock is hard for any radar to distinguish.

ii. Can such deposits be identified within/beneath large impact basins/craters?

Same reasoning as above.

iii. If so, what is the depth/distribution of these ice bodies?

An extra point for 2D for better geographic coverage.

3. Liquid Water:

i. Is there a water table on Mars and, if so, what is its three dimensional configuration?

These radars are optimized to detect water, and if water is there they should see it. So all get a 1, except MS, since precise depth determinations are difficult for MARSIS in the first few 100 m, compared to a higher resolution sounder.

ii. Do hydrothermal or other near-surface reservoirs of liquid water/brine exist? If so, what is their spatial distribution?

Similar reasoning here, limited to shallow depths.

4. Polar Layered Deposits:

i. What is the thickness, extent and continuity of the layers within the polar deposits?

PLD layers are thin, so MARSIS won't be able to say much in the shallow zone. Neither radar may be able to do this at depth, but there won't be much difference between the two.

ii. Is there geophysical evidence of prior variations in vertical and areal extent?

I don't see how a radar sounder addresses this one.

iii. Is there evidence of flow in the internal structure or other characteristic of the caps?

This wil be very hard to see. It implies deformation, which means non-horizontal layers. The orbital sounding geometry is not conducive to such structure. I suppose if you saw the reflections from flat layers disappear in some areas...but this could be due to other effects.

iv. Is there evidence of past or present basal melting or basal lakes?

Present basal melting should jump out at you. Maybe the shallow categories should be "NA" for this one, since its too cold within 1 km.

v. Are there peripheral ice deposits that may have been associated with local discharges of subpolar or subpermafrost groundwater?

This one is similar to the "frozen ground" questions above.

5. Gas Hydrates and Liquid CO2:

i. What is the 3-dimensonal distribution/concentration of gas hydrates and liquid CO2 in the crust?

Neither radar has an advantage in distinguishing CO2 from other materials, so I treat it the same as frozen ground.

6. Local and Regional Variations in Crustal Lithology and Structure:

i. What is the 3-dimensional tectonic, volcanic and sedimentary structure of the crust?

Even though it's way down the list, this may turn out to be the most important kind of data we get. There could be strong contrasts at shallow depths, so MS still would see them, just not at high resolution – so it gets a 2 not a 3.

ii. How does the porosity of the crust vary geographically and at depth?

Not going to be easy to separate this out from other effects. Porosity, composition and pore-filling material can all trade off one another to make variations in dielectric constant. Went with the default 2212.

8. Engineering constraints on addition of a radar sounder to ’05 Orbiter

There is not a baseline mapping orbit design for the Mars '05 Orbiter per se.
We do have a strawman mapping orbit under consideration –

General Characteristics:

- Sun-synchronous with an equatorial crossing time of 3:00 PM local mean solar time (LMST) (This implies a polar inclination of around ~93 deg)
- Near circular at an altitude of around 400 km (e.g. 375 km by 425 km, 350 km by 450 km). We are assumming a repeating groundtrack will be required and would derive the repeat parameters based upon science requirements. Within the range of altitudes we are considering, there the are number of options.
- We are also considering orbits with lower altitudes (e.g. 200 km x 400 km, 200 km x 200 km) The repeat cycles for these orbits are more limited. (For various reasons, I personally do no believe that we could fly a 200 km circular orbit but we are keeping the option open until we can evaluate it.)
- Assumptions on daily average data volume: Average data rate for the first 1.5 years of the mission is 20 gigabits/day, and this instrument would get 10% of that. Average data rate for the subsequent year is 60 gigabits/day, and we would get 30% of that.

period - 117 minutes
sun-synchronous
93 degree inclination

9. Technology R&D needs

We believe technologies to implement a dual-mode radar already exist, but there is a need for a short technical study to determine an optimum radar configuration including signal processing algorithms.

We believe technologies to implement a dual-mode radar already exist, but there is a need for a short technical study to determine an optimum radar configuration including signal processing algorithms. Space-qualified technology for implementing a radar with sub-band chirp readily exists. Synthesizers and arbitrary waveform generators for producing a variety of transmitter waveforms have been developed for military and civilian applications. These can be readily adopted for implementing a dual-mode radar that operates in step-frequency mode for shallow sounding and chirped mode for deep sounding of Martian soil. However, many of these latest waveform generation technologies may not be space qualified and research to space qualify these may be required. Also a detailed technical study of antenna configuration for sub-band chirp radar must be conducted to determine the effect of unused elements on the radiation pattern of the element being used for transmission and reception.

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Figure 1.

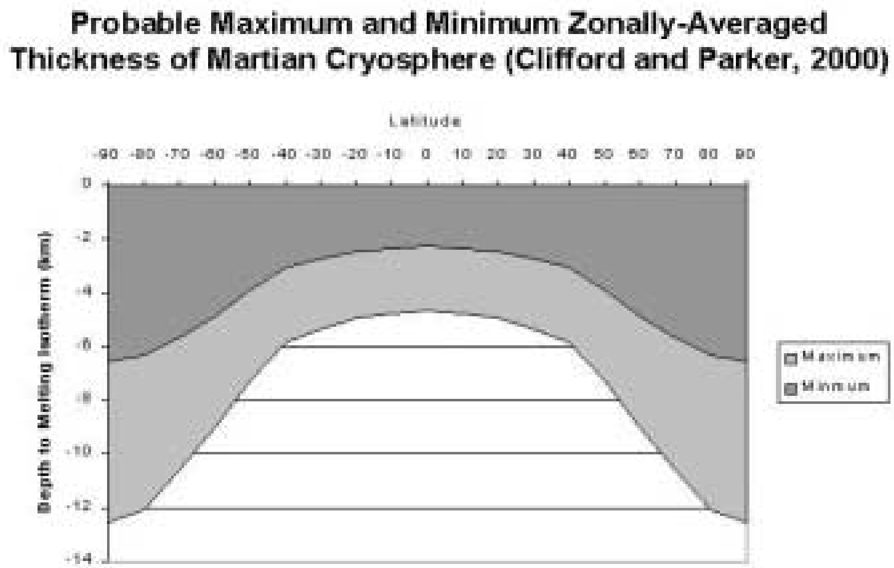

Probable Maximum and Minimum Zonally-Averaged
Thickness of Martian Cryosphere (Clifford and Parker, 2000)
Latitude
-90 -80 -70 -60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90
0
-2
-4
-6
-8
-10
-12
-14
Depth to Melting Isotherm (km)
Maximum
Minimum

Figure 2.

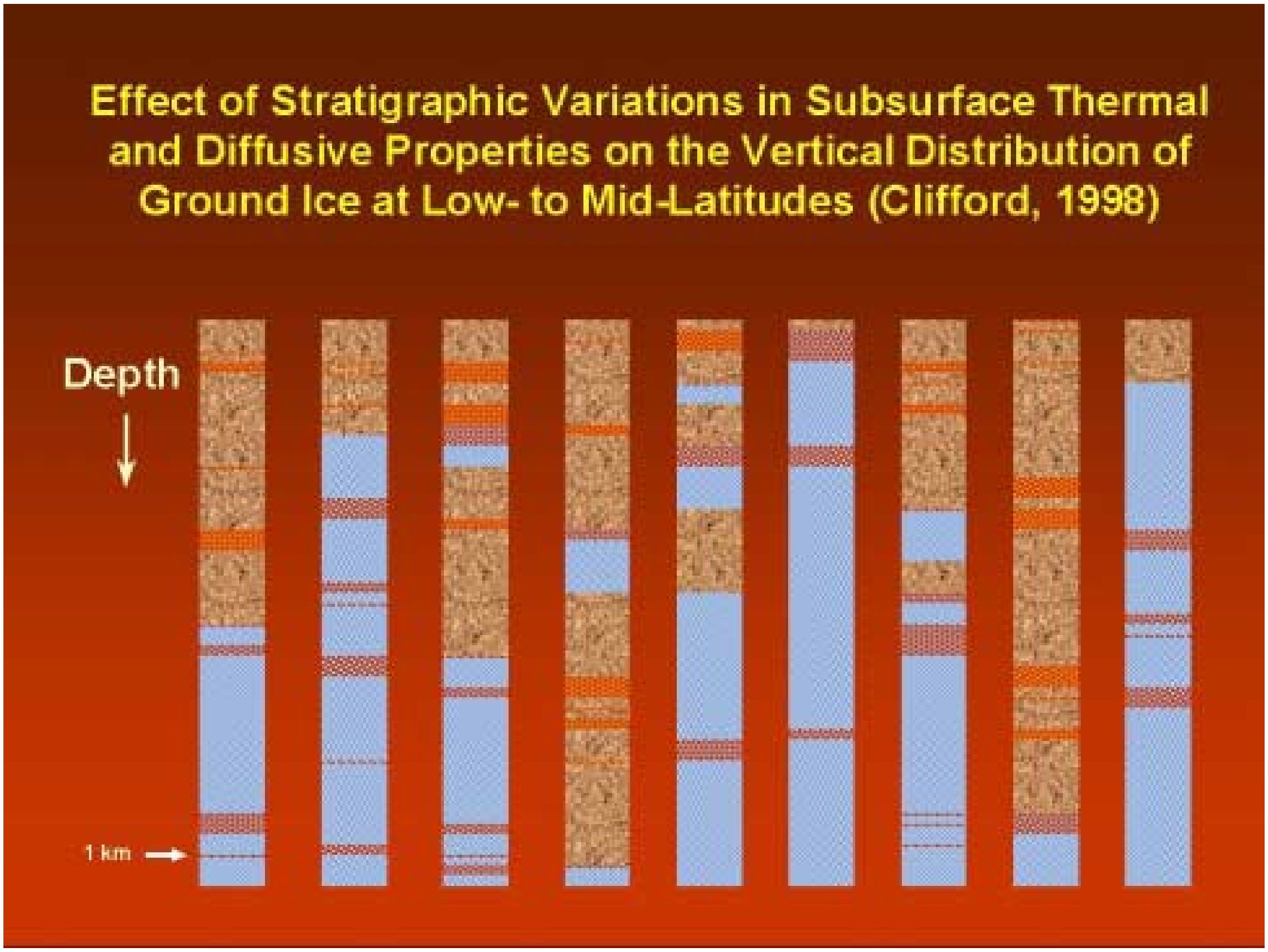

Effect of Stratigraphic Variations in Subsurface Thermal and Diffusive Properties on the Vertical Distribution of Ground Ice at Low- to Mid-Latitudes (Clifford, 1998)
Depth
1 km

Figure 3.

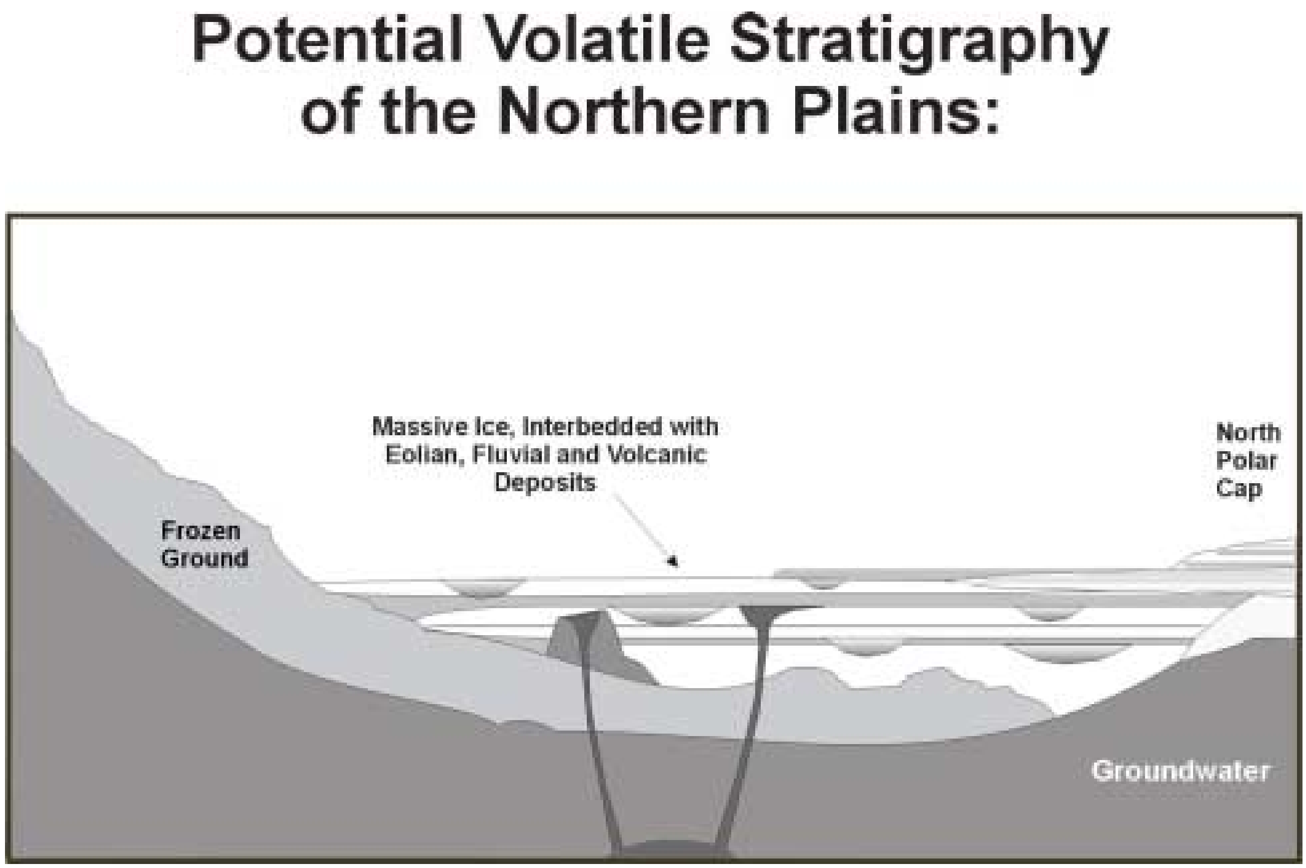
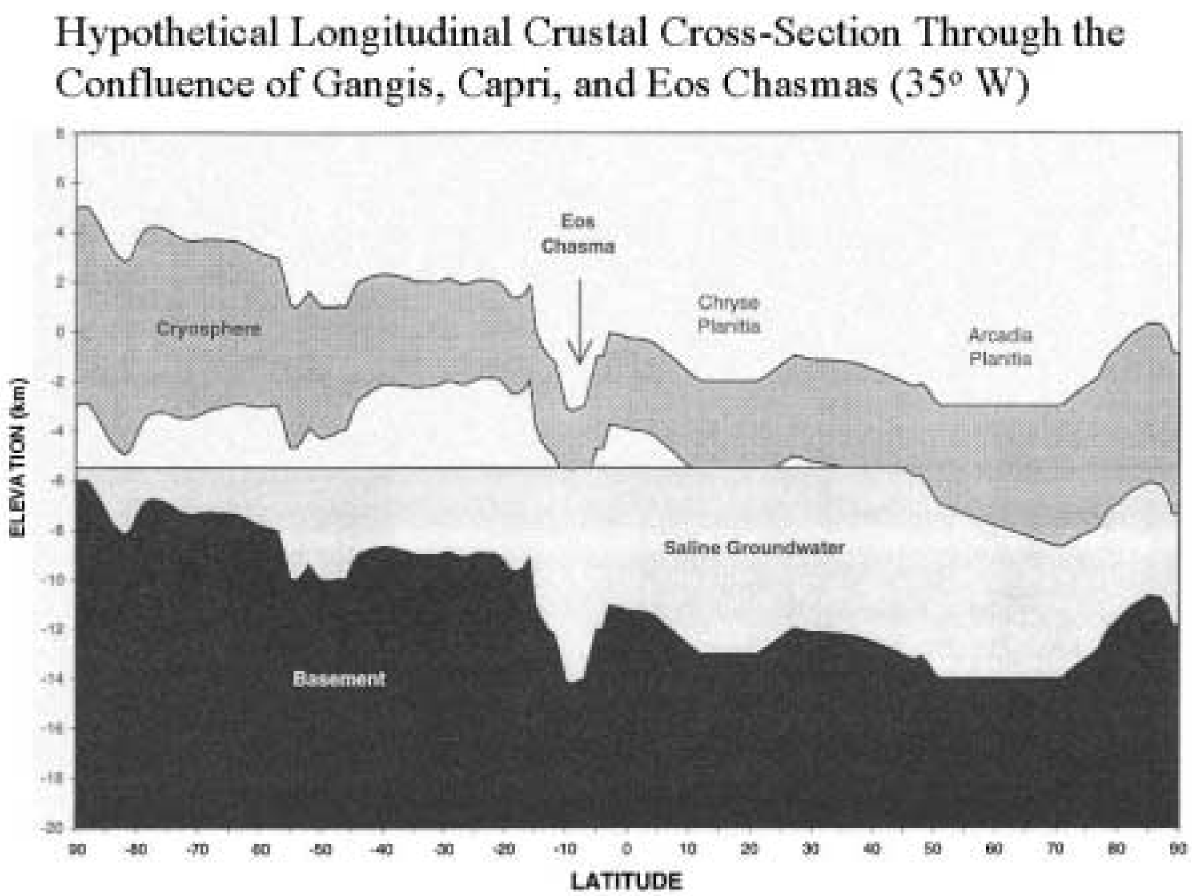

Potential Volatile Stratigraphy
of the Northern Plains:
Massive Ice, Interbedded with
Eolian, Fluvial and Volcanic
Deposits
North
Polar
Cap
Frozen
Ground
Groundwater

Figure 4.


Hypothetical Longitudinal Crustal Cross-Section Through the Confluence of Gangis, Capri, and Eos Chasmas (35° W)
Eos Chasma
Cryosphere
Chryse Planitia
Arcadia Planitia
Saline Groundwater
Basement
ELEVATION (km)
LATITUDE

APPENDIX 1: Charter (November 4, 2000)

A Mars radar sounding team will be formed to produce a white paper with analysis and recommendations on the three questions posed below. We would like to launch this team ASAP, and request that they complete their work by the end of December. The information is needed as input to decision-making related to the ’05 Orbiter. If possible, advice on the fourth question below would also be appreciated.

<u>Proposed team:</u>

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<u>The questions:</u>

1. Is there scientific value in placing a subsurface radar sounding instrument on the '05 Orbiter?

a. Assuming MARSIS delivers data in '03 as designed, what can we do that would offer an incremental step forward? (The '05 Orbiter will be in a different orbit than Mars Express, and the mass and power allocations may be different.) Would there be significant value in improving the deep sounding, in achieving finer resolution in the shallow region, or any other purpose? Is the incremental value enough that the scientific community will accept it?
b. Assuming MARSIS fails to deliver any data, what would we recommend for '05?
c. Since we won't have an answer to the success/failure of MARSIS before a commitment to a design of the '05 mission needs to be made, can the answers to the above two bullets be synthesized into a single recommended course of action?

2. If a recommendation is made for an '05 radar sounder, what are possible requirements and conceptual designs?
3. Can we put a sounder on the '05 Orbiter without significantly impacting the design of the spacecraft? This will involve discussions with Jim Graf.

<u>Extra question (if you have time)</u>

4. Are there any approaches to ground-based sounding from the martian surface in 2007 that would effectively complement orbital sounding? Is there a technique (GPR, E-M sounding, etc.) that would add value locally assuming that MARSIS shows us something?

APPENDIX 2: Capabilities of the MARSIS Radar Sounder

(from Mars Express proposal, February, 1998)

Note: The text below is directly quoted from the proposal document, with the exception that the figures and equations have been omitted. The instrument referred to below as SSRA is now known as MARSIS.

Resolution, Coverage and Data Content

The SSRA will operate in a continuous mode at all available opportunities when the Mars Express spacecraft is within 800 km of Mars. During each orbital pass, a swath of echo profiles will be gathered with a footprint size at the surface of approximately 5 by 10 km, and a footprint spacing along-track of 5 km. After about 2000 non-repeating orbits, the swaths result in full global coverage, contiguous at the equator and with substantial overlap at higher latitudes.

The flexibility in operating frequency of the instrument will allow optimization of the observation parameters depending on the conditions of the Martian environment. Data will be acquired in at least 2 frequencies at any given time. The nominal subsurface sounding mode will use frequencies of 3.8 MHz and 4.8 MHz during dayside operations and 1.9 MHz and 3.8 MHz during nightside operations. A third frequency of 2.8 MHz will be available for nightside operations, if such use of the four processing channels is deemed useful. The signals will be transmitted and processed with a bandwidth of 1 MHz, which will provide a vertical (depth) resolution equivalent to 150 m in free space. This resolution will correspond to a finer scale within the subsurface due to the difference in refractive index; nominal vertical resolution for the expected materials is about 50-100 m.

Received signals will be digitally sampled at a rate of 2.5 MHz, processed on board in range and azimuth, and stored as digital 205-sample 16-bit profiles for subsequent downlink. Details of the radio frequency architecture and digital processing scheme are provided in section 3.3. In the nominal dual frequency mode, four echo profiles will be taken for each 5 by 10 km footprint; one for each frequency, at both the primary and secondary antennas. During ground data processing and analysis, echoes from the secondary (receive-only) antenna, which are expected to arise only from off-nadir surface "clutter," will be used to remove surface echoes from the primary antenna profiles, thus isolating the subsurface reflections. Reduction of surface clutter by this technique is expected to improve the detectability of subsurface interfaces by as much as 15 dB in some cases, adding perhaps 1-2 km of signal penetration depth. As detailed in section 1.3.2 below, it is anticipated that interfaces as deep as 5 km will be detected under favourable circumstances, and that ice/water and dry/ice pore fill interfaces should be detectable for most areas if they exist in the upper 1-3 km.

For each 5 by 10 km SSRA footprint, a suite of parameters will be retrieved. The source for these parameters will be the four echo profiles (backscattered power as a function of time). During ground data processing, each footprint profile set will be analysed for surface reflectivity at each frequency, echo dispersion at the surface (an indication of surface roughness), surface elevation, time delay to subsurface reflector(s), intensity of subsurface reflection(s), and a measure of "confidence" that a subsurface interface was detected. These parameters will be incorporated into a global map database, to allow interpretation of local and regional behaviour, and for omparisons with other data sets.

Detailed analysis will be conducted for regions of interest. This will include modelling of the electrical properties of the layers and interfaces. The modelling will result in estimates of thickness of layers, depth to interfaces, dielectric properties of the materials, and an interpretation of the properties of the materials, including composition. It is anticipated that the abrupt dielectric contrasts that should exist at a Martian water table would allow an unambiguous identification of liquid water. If small (~10s of km in lateral extent) aquifers are present, the resolution and processing scheme of the SSRA should allow their detection, unlike other systems that may require extensive, uniform layer and interface conditions. Boundaries involving the presence and absence of ground ice will be more difficult to distinguish, but regional trends (with latitude and elevation) should allow discrimination of ground ice boundaries.

To carry out ionospheric soundings, we propose to transmit monochromatic pulses with a nominal duration of 50 µsec, and a pulse repetition frequency of 125 Hz, thereby giving a range resolution of about 15 km, and a maximum range of 1200 km. In order to generate ionospheric plasma frequency profiles (similar to Figure 1-3), from which the topside electron density profile can be computed, the sounder frequency must be stepped over a frequency range that extends from the plasma frequency at the spacecraft, which could be as low as 0.1 MHz, to the maximum plasma frequency in the ionosphere, which could be as high as 4.3 MHz (see Figure 1-4). As a nominal frequency scan for ionospheric sounding, we plan to step the sounder frequency over a frequency range from 0.1 MHz to 5.4 MHz in 10 kHz steps, thereby generating a sounding profile with 531 frequencies. The time required to acquire such an ionospheric profile would be 4.24 seconds, which if the soundings are repeated in contiguous sequences, would give a horizontal resolution of about 20 km.

Subsurface interface detection

Detection of a crustal interface between layers of differing material, (e.g., ice-bearing versus liquid water-bearing rock) by the SSRA requires that a set of conditions be met. The most critical conditions are:

- The interface represents a contrast in the real dielectric constant,
- Attenuation of the signal during its round-trip from the instrument and through the crust is small enough,
- The competing signals, primarily from the surface “clutter”, do not mask the subsurface echo.

In this section, we examine the implications of these requirements with respect to the depths the SSRA can be expected detect certain kinds of interfaces.

When the transmitted wave encounters the surface, a fraction of the energy is transmitted into the crust, depending on the Fresnel reflection coefficient of the upper layer. A similar fraction of any energy reflected from depth will emerge from the surface on its return path. During two-way propagation through the crustal media, energy losses will occur due to the dielectric loss properties of the media, and due to scattering by inhomogeneities. At a subsurface dielectric interface, the fraction of energy reflected depends on the ratio of the real dielectric constant across the interface. Each of these interactions is considered in the following estimation of depth detection capabilities.

In order to simulate the detection process, we have chosen combinations of materials and geometric configurations that represent a spectrum of best-case to worst-case scenarios likely to be encountered on Mars. For crustal host-rock and pore-filling materials the following end-member properties are considered:

(Table 1-5. Summary of the assumptions of Mars subsurface material properties.)

The pore-filling material is assumed to be intimately mixed with the host material in proportions determined by the porosity. The porosity fraction decays exponentially with depth, starting with surface porosities of 20% and 50% (see Section 1.2.2). The dielectric properties of the mixture are calculated using the Maxwell-Garnett formula. Two scenarios of pore-filling configurations are considered:

- Ice/water scenario: The porosity is saturated with ice from the surface down to a certain depth, below which liquid water is stable and becomes the pore-filling material.
- Dry/ice scenario: The pore-filling material is considered to be gas (Martian atmosphere) to a certain depth, below which ice fully occupies the porosity.

Attenuation due to dielectric losses can significantly reduce the energy of the wave. The following figures illustrate this effect.

(Fig. 1-5. Attenuation losses for mixtures of candidate materials in the crust at 3 MHz, as a function of depth to an interface (ice/water and dry/ice scenarios) for a) basalt host, b) andesite host.)

Scattering within the volume of the crust by inhomogeneities such as embedded clasts and fractures will also attenuate the signal. This effect will be significant if the size of the inhomogeneities is comparable to the wavelength, and if they comprise a significant fraction of the volume. Rock populations at the landing sites (Golombek and Rapp, 1997; Golombek et al, 1998), which may be considered representative of the megaregolith, do not have a sufficient component of clasts at the scale of 10s of m to affect signals at the SSRA wavelengths (62-158 m). Joints, fractures and faults within the crust may also introduce volume scattering, but this effect is difficult to quantify with current data. Extensively “shattered” regions may significantly attenuate the SSRA signal, making interface detection difficult.

As the spherical wave front propagates into the subsurface at nadir, other parts of the same wave front illuminate other areas on the surface at non-zero incidence angles. Some portion of this non-nadir surface illumination will be scattered back to the radar. While this is not a problem for smooth surfaces because the scattering law decreases very rapidly with incidence angle, for rough surfaces the off-nadir scattering contribution may be significant enough to mask the weaker subsurface echo. To quantify this effect, we model the surface backscatter as the result of a statistically characterized surface roughness, at scales relevant to the scattering phenomena.

Simple approximate methods can be applied for surfaces which present a unique roughness scale, with either a large correlation length (a gently undulating surface), or a very small rms height (a slightly rough surface) compared to the incident wavelength. Specifically, the Kirchhoff method can be applied for gently undulating surfaces, and the Small Perturbation Method can be applied to slightly rough surfaces. Validity conditions apply to these two models (Ulaby et al, 1986; Fung et al,1992). For Mars we consider the contributions to the scattering at two scales of roughness, the divide between the scales being essentially the radar wavelength. Section 1.2.3 and Table 1-4 give the range of roughness parameters of the Martian surface that were considered for the surface scattering simulation.

The surface backscatter contribution, which depends on incidence angle, can also be portrayed as function of the "equivalent depth" of the subsurface competing return, for a given dielectric medium. Figures 1-6 and 1-7 show the large-scale and small-scale backscatter contributions, as a function of equivalent depth, at the two bounding frequencies of the SSRA.

(Fig. 1-6: Large-scale scattering contribution a) 1.9 MHz b) 4.8 MHz. Correlation lengths (l) are 1500-2500 m, and rms slopes are 0.5°-5°.)
(Fig. 1-7: Small-scale scattering contribution a) 1.9 MHz b) 4.8 MHz. Rms heights (sh) are 0.1-1 m, and rms slopes (rms) are 6°-34°.)

Figure 1-6 shows that for the large scale, the decay rate of the surface term depends mainly on the rms slope value. There is also no significant variation with frequency. For the small scale, Fig. 1-7 shows substantially no decay of the backscattered power with the incidence angle. Interactions between the two different scales must be taken into account when combining the two contributions. No significant variation of the small-scale term is expected with large-scale tilts, because of the small incidence angles and small large-scale rms slopes. As a consequence the mutual interactions between the large and small scales are very weak, and the total surface backscatter can be evaluated in first approximation by simply summing up the two scale contributions. Examining of the figures and considering that a maximum dynamic range of 60 dB is expected for the SSRA, the surface clutter contribution will likely be the limiting factor for the penetration depth for the roughest large-scale surface conditions, i.e., when the rms slope is
bigger than 3-48 (0.05-0.06 rad.).

Under the simplifying assumption of small fractional bandwidth, the Fresnel term of the echo reflected by the subsurface interface can be expressed as (Porcello et al., 1974):

(equation here)

where the first factor represents the reflection loss on the subsurface layer interface, the second factor accounts for the losses due to transmission through the surface layer and the last term indicates the loss due to the propagation of the signal into the upper layer from depth 0 to the depth of the interface.

We have modeled the performance of a simple radar sounder, first utilizing only along-track Doppler filtering for reduction of surface clutter. The following charts show the expected level of returns from subsurface interfaces attenuated by the intervening layer (heavy line), compared with the surface returns that arrive at the same time. The depth at which the subsurface line intercepts the surface line indicates the maximum detection depth for that scenario.

(Fig. 1-8. Interface detection simulations in the presence of surface clutter for a simple sounder. These results are for a basalt host rock with a surface porosity of 35%. a) ice/water interface at 1.9 MHz, b) ice/water interface at 4.8 MHz, c) dry/ice interface at 1.9 MHz, d) dry/ice interface at 4.8 MHz.)

These simulations show that although some of the smooth surface scenarios allow detection of interfaces to depths up to 3 km, the surface clutter masks the subsurface echo in many situations. Utilising a second receiving antenna with a nadir-null antenna pattern can be shown to reduce the strength of the surface term by 10-20 dB, depending on the surface roughness. The improvement factor in clutter cancellation by this technique can be expressed as (van Zyl, 1997):

(equation here)

where g1(.) and g2(.) represent the uncertainty in antenna pattern knowledge (as a function of incidence angles) for the primary and secondary antennas, respectively. Note that this factor depends only on the knowledge of the antenna patterns, not the pattern functions themselves.

If subsurface echoes are received at two frequencies, they should be fairly different in power, thanks to the material attenuation which is linearly (in dB) dependent on the frequency. Hence if the surface contribution at the two frequencies is similar, it is possible to both estimate the ratio of Fresnel reflection coefficients at the subsurface interface, and to reduce the surface clutter contribution by properly combining the echoes received at the two frequencies. The surface clutter suppression factor using the two frequency approach can be in the range of 10-30 dB.
The following table summarizes the maximum detection depth for Ice/Water interface and the range of subsurface characteristics considered, at the four operating frequencies of the SSRA. Values were derived from calculations that included the effects of surface clutter cancellation.

APPENDIX 3: MARSIS Experience and Technical Issues In Implementing A Radar Sounder

The purpose of this section is to provide some technical information that may be helpful in exploring different scenarios for future radar sounder missions to Mars.

MARSIS Background

MARSIS is a low-frequency sounder optimized to achieve its science goals within the allocated mass, power and implementation time requirements specified by Mars Express spacecraft. To understand the design philosophy which will be outlined in the following, we need to state the instrument's science objectives.

MARSIS Science Goals

Primary:

To detect water (if it exists) in the first 5 km of the Martian surface.

Secondary:

To characterize Martian ionosphere using ionospheric sounding techniques

To achieve the primary objective, MARSIS is designed as a low-frequency (1.3 MHz – 5.5 MHz) system with 1 MHz bandwidth for each individual channel in the subsurface sounding mode. The choice of frequency is dictated by the expected attenuation characteristics of the Martian subsurface that is currently estimated to be 4-10 db/km for frequency range of 1.5 to 6 MHz. A doubling of frequency will roughly double these attenuation rates.

To achieve the secondary goal, MARSIS is capable of sounding the ionosphere at any frequency from 0.1 MHz to 5.5 MHz using a 10 KHz tone.

MARSIS instrument has a single transmitter with 3 distinct matching networks for the following bands:

3. 0.1-1.3 MHz
4. 1.3-2.3 MHz
5. 2.5-5.5 MHz

There are two receive channels which accommodates a dipole and a monopole antenna. The transmission is only through the dipole channel.

There is a dedicated on-board processing capability using two DSP chips. The on-board processing is required for data reduction and on-board chirp compression and ionospheric compensation for tracking and acquisition.

MARSIS Constraints

Mass	15 kg
Power	70 W
Antenna Length	40 m dipole
Maximum E-Field Emission	50 v/m
Orbit	~8 hr elliptical orbit with 30 minutes below 800km altitude
Sun	Mostly daytime operation with no deep night access

MARSIS Science Processing Philosophy

The current form of the MARSIS science processing unit is the result of a balance between downlink data rate and science data quality. It is preferable to reduce the raw data as much as possible to reduce the data rate to the ground. However, there is a point beyond which the science content of the data is seriously impacted. For example, MARSIS radar data is affected by the Martian ionosphere. A correction for the ionosphere is necessary for both radar operation and science processing. Since processing resources on-board are limited, a special on-board processing scheme was designed to allow downlink of the data in a form that would make it possible to do a more accurate ionospheric compensation on the ground. An on-board ionospheric correction scheme is still implemented for radar operation purposes but its accuracy does not need to reach the level required in the science processing step.

Radar Sounder Design Issues

MARSIS is designed to image subsurface to a depth of 5 km with a resolution of about 100 m. This system is not well-suited for studying near surface features in the first km of the surface. In order to design a system to probe the near surface effectively, the following issues, among others, have to be addressed:

A. Low frequency operation through the ionospheric
B. High relative bandwidth (e.g. 5 MHz at 5 MHz center frequency)
C. Innovative high-bandwidth antenna dipole design
D. Controlling the spacecraft generated EMI and reducing spacecraft susceptibility to E-field generated by the radar
E. Capability to store raw data during radar operation possibly as much as 0.5 -1 Gbits
F. Capability to have adjacent orbits for two-dimensional analysis of data

All of the above items can be overcome given sufficient time. We believe it is possible to meet the ‘07 or ‘09 mission requirements, however, meeting the requirements for an ’05 mission requires a more rigorous study.

Low Frequency and Ionosphere

Low frequency of operation is imperative in order to obtain depth of peneteration. However, this requirement is contradictory to the ionospheric limitation which prohibits us from operation at frequencies close to the peak plasma frequency. Based on our current knowledge, the dayside operation is limited to frequencies above 3.5 MHz. The night-side operation may be possible at frequencies as low as 1 MHz.

The Martian ionosphere will degrade the signal by 1) attenuating the signal and 2) dispersing the signal. The attenuation level depends on the solar zenith angle. The attenuation levels may be too high for dayside operation. The ionospheric dispersion degrades the final image resolution and signal-to-noise ratio. The correction for the dispersion can be applied on-board, however, an accurate correction for ionospheric correction is possible on the ground. In the MARSIS design, the dedispersion process is carried out on-board for tracking and signal acquisition purposes and the science data is dedispersed on the ground. The choice to carry out the dedispersion of the science data on the ground will not increase the data rate since the along track processing will still be carried out on-board.

High Relative Bandwidth

MARSIS has a 1 MHz bandwidth which will yield roughly a 100 m resolution for subsurface. We need at least 5 times as much resolution if we are focusing on the first one-km and are looking for finer details.

The driving factor in this design is the total bandwidth of the radar. Let’s consider an overal bandwidth of 4.6 MHz. This system has four bands each 1.3 MHz wide with 0.2 MHz overlap between the bands. Assuming a refractive index of 2.2, the nominal resolution in the medium is 16 m.

Due to high relative bandwidth of the proposed system, the wide-band antenna and transmitter matching will be challenging. In order to achieve the best matching and radiation efficiency, the antenna can be made of four separate dipoles within the same physical structure. Each of the dipoles will be matched through its dedicated matching network with the transmitter.

The receive channels include four independent receivers connected to the corresponding dipole antenna.

Innovative Antenna Design

The relative large operational bandwidth will require new approaches in designing the lightweight antenna. This item will be described in more detail in Appendix 4.

EMI and Susceptibility Requirement

Radars generate large E-field and require very quiet environment for detecting weak signals. Both of these issues will push the spacecraft EMI requirements to the limit.

Raw Data Storage and Downlink

Due to complications of ionosphere, a high quality processing can only be achieved on the ground. This means at least part of the data needs to be preprocessed on-board and then downlinked for further analysis on the ground. This will increase the need for larger storage on board (e.g. using compact flash, etc).

Along Track Resolution

The along track resolution by a radar sounder depends on its frequency of operation, synthetic aperture size, and more importantly, the surface characteristics. For Mars, considering available surface roughness information from recent MOLA data, the ideal sounder resolution is between 1-5 km. An instrument design for a better resolution will not be able to fully utilize its capabilities.

Improving SNR

A sufficiently high signal-to-noise ratio (SNR) is paramount in achieving the science goals of the mission. The main method for improving the SNR is signal averaging either through chirp compression, presumming or a combination of the two. Raising the instantaneous output power, although effective, is not practical because of engineering limitations on peak power levels. Increasing the SNR either through long-chirp implementation or high PRF design will translate into higher average power consumption and a higher processing load. MARSIS has a maximum dynamic range of 46 db which is achieved by using a long-pulse scheme at low PRF. Due to recent information about the Martian surface roughness and backscattering characteristics, it is possible to consider a higher PRF system with shorter pulse length since range ambiguity is not going to be a problem.

Clutter issue and Two-Dimensional Aperture synthesis

The issue of clutter for near surface may be a serious limiting factor. Further, many of the points of interest, as demonstrated so far, may lie in rough areas or at the crater rims. Radar sounding processing over this type of sites requires access to a two-dimensional aperture which may be obtained through adjacent orbit data. This type of data processing is possible on the ground if raw data mentioned in the above section is provided.

High Resolution Radar Sounder

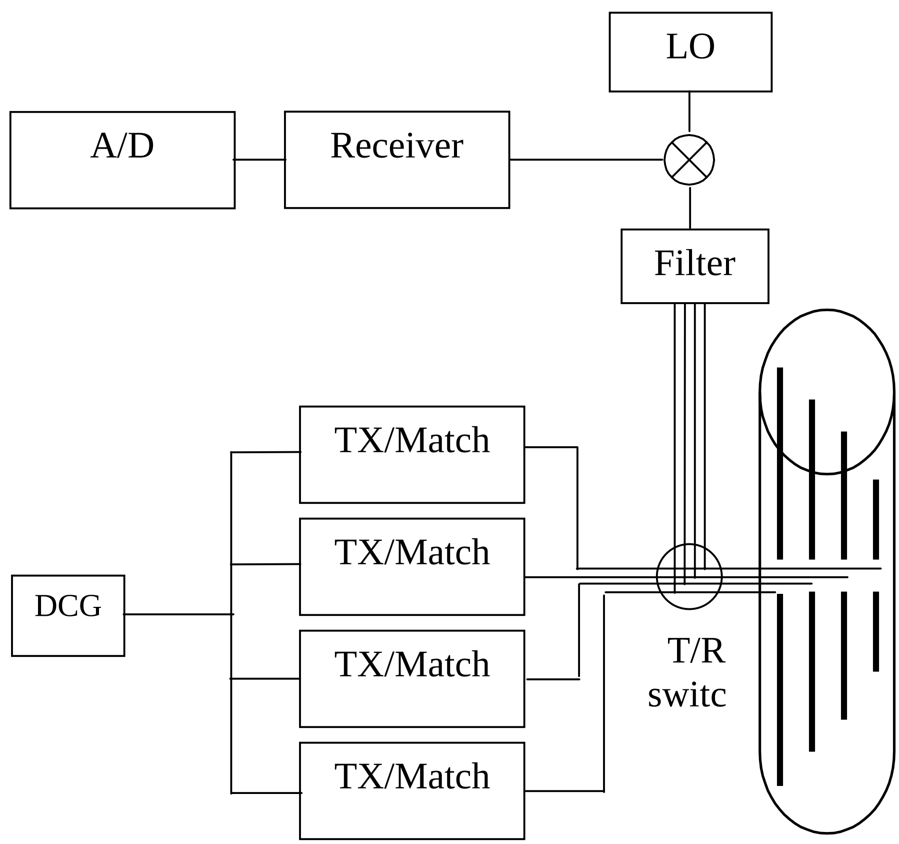
A radar capable of sounding the first 1 km of the surface can provide valuable science return. This radar sounder will also be complementary to MARSIS. One of the main challenges in implementing such a radar is to achieve high bandwidth at low frequencies. We believe the bandwidth and the clutter issue to be the primary challenges in implementing a shallow sounder.

APPENDIX 4: A Design Based on The MARSIS Heritage: Wide-band Multi-channel Radar

This option builds on MARSIS heritage but makes appropriate modifications to make shallow sounding possible. As mentioned in Appendix 3, the main requirement for shallow sounding is higher vertical resolution, which requires a larger bandwidth. MARSIS provides a large bandwidth of 4 MHz through its four subsurface sounding bands. However, these bands are not continuous and are not easily combined to allow larger effective bandwidth. In this design, we propose a radar with multiple bands similar to MARSIS but we allow for overlap between the bands and further allow for near-simultaneous operation.

Multiple Transmitter and Antenna

For example, the transmitter/antenna system can be a set of four independent channels with each optimally tuned for a given band as shown in the Figure below.



The existence of four dipole wires (one for each channel) will significantly enhance transmitter/antenna coupling and increase radiation efficiency. This is a significant difference from the MARSIS design. This advantage is gained with minimal implementation and mass penalty since all of the dipole wires will be within the same physical structure which needs to be as long as the longest dipole.

The frequency channels may be continuous or disjointed based on the measurement objectives. We envision the bands be overlapping and cover a continuous frequency band. An example of such a frequency band selection is given in the following table. There are a total of four bands with the lowest frequency at 1.4 MHz with a 1.3 MHz bandwidth. Each band is overlapping the other by 0.2 MHz. This overlap will assure cross-band calibration and frequency continuity.

Band	Start Frequency	End Frequency
1	1.4	2.7
2	2.5	3.8
3	3.6	4.9
4	4.7	6

Operation Modes

Two distinct operation mode are considered:

1. Shallow sounding mode (surface to 1 km)
2. Deep sounding mode (surface to 5 km)

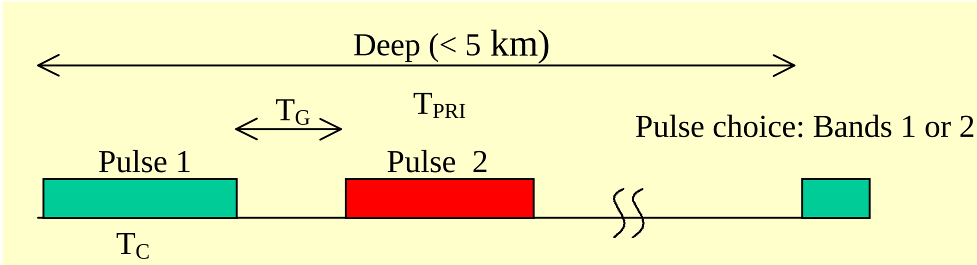
The radar will operate with full bandwidth at the shallow sounding mode and at reduced bandwidth at the deep sounding mode.

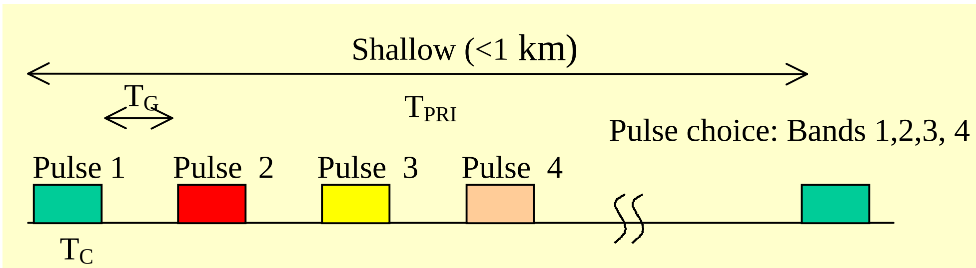
An example of the pulsing scheme is shown below. In the propose pulsing scheme, a single fixed PRF (pulse repetition frequency) is assumed. However, the pulsing scheme within the PRI (pulse repetition interval) can be changed depending whether the operation is in the deep or the shallow mode.

In the deep sounding mode, within a given PRI two longer chirps are transmitted with an effective bandwidth equivalent to one or two bands depending whether pulse 1 and 2 are from the same band or different bands.

In the shallow sounding mode, there are four shorter chirps covering all or a subset of bands. This mode will have the highest possible system bandwidth.

The PRF is selected such that there is only one set of pulses in the air at a given time. This will mean this design will have a PRF of few hundred Hz (200-300) depending on the orbit altitude choice. In order to improve SNR, the total transmitted energy is maximized by increasing the chirp length to maximum allowed.





Antenna

Based on the lowest band frequency selection, an optimum antenna length is about 60 m. Currently, MARSIS is employing a 40 m dipole antenna along with a 7 m monopole antenna.

Mass and Power Estimate

Based on our experience with MARSIS radar that has a mass of 15 kg, it is expected that the proposed radar will have a mass of 20 kg with 5 kg margin (or 25 kg). Based on the 2005 orbiter design team comments, after inclusion of the 20 kg radar, spacecraft can still maintain a 28% mass reserve.

Also, Extrapolating from the MARSIS power requirement, it is expected that the proposed radar will require 100 W for its operation. Based on comments from the 2005 orbiter design team, this requirement should be easily met.

Possible Orbit Requirements

A lower orbit is favored by a radar sounder since it provides better SNR and better along track resolution. For this design, a circular orbit at 250 km is preferred but in the absence of this option, an elliptical orbit of 250 by 450 is acceptable.

An adjacent orbital separation of 3 km or less at the equator is desired to achieve two-dimensional aperture synthesis capability over certain “focus areas”.

APPENDIX 5: Independent analysis prepared by ASI.

Editorial note: The following analysis was prepared by the technical staff in ASI under the leadership of Angioletta Coradini, and submitted on Jan. 16, 2001. It is incorporated here verbatim, so that the ASI perspective can be clearly framed. This analysis has not been completely validated by the other authors of this report. If there are questions, please contact:

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Introduction to the description of the High Resolution Sounder

The new knowledge developed thanks to MGS indicates that sedimentary processes are more complex than anticipated before, and that they are possibly related to the water history on Mars. Moreover some of the MOC images seem to indicate the presence of shallow ice/water reservoirs. Given the nominal characteristics of the 2005 mission, one can envisage an instrument to support investigations that complement the results of MARSIS. An instrument able to penetrate a few hundreds of meters below the surface with a finer horizontal resolution and a vertical resolution (on the order of 10 m - 20 m) would provide a unique insight into the Martian stratigraphy at scales comparable to those of optical images, thus offering a tremendous improvement in the understanding of sedimentary processes and recent geologic activity.

A concept for such a radar sounder has been developed and is presented in below. The study for the definition of a lower-penetration, higher-resolution radar (or channel) has been performed under the assumption that the modeling of the radar pulse propagation in the subsurface that was performed for the MARSIS experiment can be extended to shorter, yet comparable, wavelengths.

An important point in this design is that only one matching circuit is necessary for the transmission at the different frequencies of operation, so that the “real stepped frequency” technique can be used, without decreasing the PRF, thus allowing clutter cancellation by use of Doppler filtering. This reduced complexity, together with the smaller antenna allowed by the use higher frequencies, translates into a reduction of the required mass: current estimates allow for a 40% mass reduction with respect to MARSIS.

The benefits of operating at higher frequencies are summarized in Section 4 C. Additionally, there is also a significant reduction of the impact of the instrument on the spacecraft, in terms of electromagnetic compatibility, as shown in the 1/8/01 memo by A. Whittlesey on the MRO EMC needs.

The Mars High Resolution Advanced Radar for the 2005 MRO

The new knowledge developed thanks to MGS indicates that sedimentary processes are more complex than anticipated before, and that they are possibly related to the water history on Mars. Moreover some of the MOC images seem to indicate the presence of shallow ice/water reservoirs. Given the nominal characteristics of the 2005 mission, one can envisage an instrument to support investigations that complement the results of MARSIS. An instrument able to penetrate a few hundreds of meters below the surface with a finer horizontal resolution and a vertical resolution (on the order of 10 m - 20 m) would provide a unique insight into the Martian stratigraphy at scales comparable to those of optical images, thus offering a tremendous improvement in the understanding of sedimentary processes and recent geologic activity.

For these reasons, a concept for a radar sounder in the ’05 MRO mission has been developed according to the following high-level parameters:

Penetration Depth:	300 m –1000 m
Vertical Resolution	10-20 m
Horizontal resolution	300 m-1000 m

The study for the definition of a lower-penetration, higher-resolution radar (or channel) has been performed under the assumption that the modeling of the radar pulse propagation in the subsurface that was performed for the MARSIS experiment can be extended to shorter, yet comparable, wavelengths.

Although a multitude of different chemical compositions is present at the surface of Mars, it is necessary to select a few representative materials as most meaningful for electromagnetic studies. We have chosen (following the MARSIS proposal) andesite and basalt, because the values of their dielectric constant can be considered end members of the range in which the first layer of the Martian surface materials may vary.

The dielectric properties of the crust end-member materials, together with those of the water and ice filling the pores, are listed in the following table:

	CRUST MATERIAL		PORE-FILLING MATERIAL	
	Andesite	**Basalt**	**Solid H_2O (Ice)**	**Liquid H_2O (Water)**
ε_r	3.5	*7.1*	*3.15*	*88*
Tan δ	*0.005*	*0.014*	*0.00022*	*0.0001*

Tab. 1: Summary of the subsurface material dielectric properties.

The reference model representing the most likely detection scenario is the following:

Ice/water interface detection scenario: according to the model, the porosity of the Martian regolith is maximum at the surface and its decay with the increasing depth is given by the exponential law with a decay constant that can be assumed of the order of 2.8 km.

The pores are filled with ice from the surface down to a depth below which liquid water is stable and becomes the pore-filling material. The change of the pore-filling material causes a discontinuity of the overall dielectric constant, which can be detected by the radar sounder.

This model will be used to estimate the penetration performance under typical operative conditions.

We will thus characterize Mars' *surface geometric structure* in terms of a *large-scale* morphology on which a *small-scale* geometric structure, due to rocks, is superimposed. The terms *large-scale* and *small-scale* refer to different approximations in the modeling of the radar backscattering coefficient: the divide between *large-scale* and *small-scale* is essentially the radar wavelength. Taking into account that recently attempts have be made to describe the structure of the planets surface by means of fractals, it is assumed that the surface can be described as a random distribution of heights, characterized by a variance σ_h, a correlation length l, a surface RMS slope m and a fractal dimension.

Topographic data can be used to derive the *large scale* geometry of the Martian surface. The global topographic maps of Mars currently available are compiled from the results of several different types of measurements which have different resolutions and different sources of uncertainties. These data not provide a complete, global picture of Mars' topography, but allow us to infer that elevation changes, although relevant in magnitude, do not involve average slopes bigger than 1°, and often much less than that. Also, the correlation lengths for the topography appear to be rather large, perhaps of the order of some kilometers.

To characterize the surface geometry at *scales smaller* than the radar measurements resolutions, it is necessary to make use of proper data sets: measured values for Mars are in the range from 0.7° to 13°, averaging at 2°, with a remarkable diversity from place to place over the surface of the planet. Such values refer to scales that, according to model interpretations, range from a few tens to a few hundred meters.

To summarize, a plausible range for the parameters describing the surface geometry is listed in the table below.

LARGE SCALE MODEL		**SMALL SCALE MODEL**	
RMS slope	Correlation Length	RMS Slope	RMS height
< 0.02 rad.	*200 – 10000 m*	*0.1 – 0.5 rad.*	*0.1 – 1 m*

Tab. 2: Summary of the values range for the geometric parameters of the surface

In the following analysis the spacecraft orbit will be assumed circular with a tangential component of the velocity of the order of 4 Km/sec.

Measurement Concept and Performance Evaluation

To assess the interface detection performance of the Radar Sounder it is required to evaluate the back scattering cross sections of concurrent echoes coming from the surface and subsurface layers. These can be expressed as $\sigma_s = \Gamma_s f_s(\sigma_{h,s},L_s,\lambda)$ and $\sigma_{ss} = \Gamma_{ss} f_{ss}(\sigma_{h,ss},L_{ss},\lambda)$ being Γ_S and Γ_{SS} the Fresnel Reflectivity terms, which deal with the surface and subsurface dielectric properties and f_s and f_{ss} the geometric scattering terms, which deal with the geometric structure of the surface and subsurface. In the following sections we will evaluate both the Fresnel terms and the geometric scattering terms using the simplified reference crust models introduced previously.

According to well known results of electromagnetic theory the Fresnel reflectivity for nadir incidence on the surface can be expressed as follows:

(1) $$\Gamma_S = \left| \frac{1 - \sqrt{\varepsilon_{r1}(0)}}{1 + \sqrt{\varepsilon_{r1}(0)}} \right|^2 = R_{01}^2$$

being $\varepsilon_{r1}(0)$ the real dielectric constant of the crust evaluated at the surface (z=0).

The models given in section 2 entail the surface reflectivity ranges between -7 dB and -15 dB, depending on the surface composition and porosity and has a typical value of –10 dB for most scenarios.

The Fresnel reflectivity for the subsurface layer located at depth z can be expressed as follows:

(2) $$\Gamma_{SS,z} = R_{12,z}^2 \left(1 - R_{01}^2\right)^2 10^{-0.1\int_0^z \alpha(\zeta)d\varsigma}$$

being $R_{12,z}^2$ the reflection coefficient of an interface located at depth z:

(3) $$R_{12,z}^2 = \left| \frac{\sqrt{\varepsilon_{r1}(z)} - \sqrt{\varepsilon_{r2}(z)}}{\sqrt{\varepsilon_{r1}(z)} + \sqrt{\varepsilon_{r2}(z)}} \right|^2$$

and $\alpha_{dB/m}(\zeta)$ the two-way unit depth attenuation due to dielectric dissipation in the crust, expressed in dB/m:

(4) $$\alpha_{dB}(\varsigma) = 1.8 \cdot 10^{-7} f_0 \sqrt{\varepsilon} \tan \delta$$

Taking into account the models of section 2, a preliminary evaluation of the Fresnel reflectivity terms for the subsurface layer entails to the following values below the surface terms::

(5) (0-10) dB + (2.5-6) dB/Km*MHz

By considering a depth investigation requirement of 300 m and a useful dynamic range of the signals of 50 dB a transmitted frequency of 20 MHz can be used, and ionosphere propagation problems are strongly reduced.

The required bandwidth should be of 10 MHz in order to obtain a range (depth) resolution of 15 m: the antenna matching circuits should be easer than in the MARSIS case.

The minimum surface back scattering coefficient (for nadir incidence) can be computed using a worst case RMS slope of 0.02 rad (Tab.2) and the lower value of Γ_s , according to the geometric optics we have:

(6) $$\sigma^0 = \frac{\Gamma_s}{2m_s^2} \qquad \sigma^0\Big|_{dB} \geq 16dB$$

The SNR equation can be written, by considering incoherent backscattering model, [1] as:

(7) $$\frac{S}{N} = \frac{P_p G^2 \lambda^3 \sigma^0 \sqrt{2\Delta} DC}{(4\pi)^3 H^{2.5} KTv_0}$$

and the minimum signal to noise ratio is shown in the attached table, taking into account very preliminary design parameters.

	H=400 km
	DB
P_p (10 W)	10
G^2	0
λ^3	41
σ_0	16
$64\pi^3$	-33
$H^{2.5}$	-140
K(1.38 10^{-23})	228
T_e=TF ***Kraus Mod.***	-49
$\sqrt{2\Delta}$ (Δ=10 m)	6.5
D.C. (20%)	-7
v_0 (4 Km/sec)	-36
Single Look S/N	**36.5**

In order to obtain the spatial resolution, in along track direction, of the 300 m it is necessary to apply the SAR approach and the synthetic aperture is given by :

(8) $$R_{AZ} = \frac{\lambda H}{2L_s} \qquad \rightarrow \qquad L_S = 10 \text{ Km}$$

The application of the synthetic aperture entails the reduction of the surface clutter.

The selection of the pulse repetition frequency, in order to avoid spectral aliasing, is given by the:

(9) $$PRF = 2*2\, v_0 / \lambda = 1/T \quad \rightarrow \qquad v_0 T = \lambda / 4 \cong 4 \text{ m}$$

The 4 m given the space in the orbit to perform radar interrogation, and the values of PRF (200-1000 Hz) not allow to use an “useful” step frequency concept.

The same synthetic aperture concept must be applied in cross track direction, so that we need radar return echoes, on ground, from many orbits.

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