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MARTIAN OASES?
FEASIBILITY OF ORBITAL THERMAL EMISSION DETECTION

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We review the motivation for searching out modern "oases" on Mars, and examine methods of detecting them from orbit. We use the term "oasis" to refer to sites with anomalous thermal behavior at, or near the planet's surface. Such sites may be more likely than other locations on Mars to have liquid water nearby, hence the terminology reminiscent of Earth's deserts. Three types of "oases" are considered here: small-scale volcanic eruptions, hot springs, and subsurface intrusions. The general consensus is that such oases are highly unlikely on Mars today, and probably do not exist at all. How much investment is worthy of such a high-risk, unlikely return? We argue that the potential long-term importance of such a discovery does merit a significant investment. We propose a detection strategy based on a high spatial resolution infra-red thermal emission instrument, though other techniques are briefly discussed. We conclude that such an instrument could feasibly detect surface lavas, and quite likely any surface hot springs, but would not be able to unambiguously determine the presence of a buried geothermal anomaly that does not manifest itself sufficiently at the surface in one of the two other forms.

INTRODUCTION

Martian "oases," if they exist, would be terribly important for the future of Mars exploration. Finding a geothermally or volcanically heated location on Mars would revitalize geophysical and geological thinking about the planet. A small "hotspot" would be a prime site to search for traces of liquid water in the Martian subsurface, and therefore also a prime spot to test for near-surface extant life. Such a location would be a prime site for a sampling mission, or even a sample return mission, and potentially also for a later human mission.

The current NASA Mars exploration timeline plans two spacecraft to Mars at each launch opportunity. At present the plan provides for a sample return mission at the 2005 opportunity. The site selection for a sample return could be significantly affected by the presence of present-day geologic activity on Mars. The current consensus in the Mars science community however, is that Mars is essentially dead as regards high heat-flow geothermal activity. It is our contention that this has not been established with sufficient

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certainty, and that the potential scientific value of a sample from a geothermally active location for example is so significant that it justifies an investment in the high risk endeavor of surveying the planet for such locales. Furthermore, the technical achievement of a sample return mission from Mars requires the demonstration of not only the aerobraking technique (lowering the spacecraft's orbit using the planet's atmosphere when it is already circling the planet) that will be used by Mars Global Surveyor (MGS), but also of the technique of aerocapture (inserting the spacecraft into a planetary orbit using the planet's atmosphere). This latter milestone has been proposed for the 2001 Surveyor orbiter, and would have the effect of reducing the fuel mass of the spacecraft, and potentially increasing its payload by up to 10 kg. Thus, we see an opportunity for the proposed "oasis" survey in 2001, leading toward the sample return mission later in the first decade of the 21st century.

Certainly, in light of recent announcements of possible microfossils within the ALH84001 meteorite [McKay *et al.*, 1996], it seems that if there is a remote chance of extant life on Mars, it should be pursued. If a sample could be returned to Earth with similar structures, it would be a stupendous achievement in Mars exploration. Of course the structures observed by McKay *et al.* [1996], need not be life, but understanding the formation of carbonates on Mars will be critical to understanding their findings. That water would be associated with a thermal anomaly on Mars is perhaps the most likely link in a chain leading to aqueous carbonate formation that we might expect. The step beyond that to life-related carbonates will take much more study. The point remains however that liquid water at or near the surface of Mars today would be an enormously compelling discovery, and the place to look for it would be near any thermal anomalies. Having reiterated the enormous potential significance such a discovery would have, we suggest that it would be worth the long-shot investment of one instrument on an orbiter (e.g. 10 kg mass, costing $10 million.) In the longer term, and in the context of future human exploration of Mars, the location of water at or near the surface is a critical resource availability question that needs to be addressed.

In the rest of this paper we will review our definition of "oasis" and give some further details of their potential significance. We will examine possible properties or types of "oases" and their relative plausibility. Then we will ask how such oases could be detected from Mars orbit? We examine the feasibility of using a high resolution thermal emission detection system with significant on-board processing to survey the planet. We also review how big an oasis would have to be to have been seen by the Viking Infrared Thermal Mapper (IRTM), or to be seen by the MGS Thermal Emission Spectrometer (TES), or by the '98 Surveyor Pressure Modulator Infrared Radiometer (PMIRR). We will briefly review other detection methods, and then discuss our implementation of a survey instrument.

OASES

We have chosen the term "oasis" in loose analogy to the Earth's desert regions to refer to a location where liquid water is possible. Since water is a solid at Mars surface conditions, in the present context "oasis" then refers to a geothermally anomalous region. Much modeling of the behavior of liquid water and ice on the surface of Mars has been carried out, in particular to attempt to explain catastrophic flood features that are clearly observed in Viking images [Baker *et al.*, 1992; Squyres *et al.*, 1992]. The models often assume a locally or regionally elevated geothermal flux to account for the initiation of flooding.

In more general terms we can expand our definition of oasis to refer to Martian "heat islands." We delineate three levels of activity for heat-island oases. Type 1: perhaps the most exciting form which such an oasis could take would be that of erupting lava. In that particular case we might not expect to find water directly, but the heat of the eruption would certainly melt nearby permafrost on the way up. Type 2: if the molten rock remains below the surface in a lava chamber, the heat coming from the chamber as it cools may drive a hydrothermal system that does reach the surface, where hot liquid water or steam erupts, heating the nearby surface. Type 3: a sub-surface intrusion, as in the previous case, could be driving a hydrothermal system, but one that does not reach the surface. Nevertheless, in this last case some thermal anomaly must still reach the surface.

For the purposes of assessing the detectability of Martian thermal anomalies, we quantify a nominal model for each of the three types. We take the temperature of lava (type 1) to be T_{hot}=1,000 K. A geyser (type 2) would produce steam, which would heat adjacent rocks, so we assume a hydrothermal vent temperature of T_{hot}=350 K. This temperature may also correspond to that of a few hour old crust on top of a lava flow. Finally for the case of a buried geothermal source (type 3) we assume only a 10 K enhancement over a Martian average of 220 K, so that for the third type of heat island T_{hot}=230 K.

How big might such heat-islands be? Wilson and Head [1994] note that Mars' lower gravity would permit larger intruding magma bodies to ascend more slowly than on Earth, but to shallower depths. Thus, we might expect that a type 1 oasis in the form of a surface lava lake could be as big or larger than its terrestrial counterpart, measuring perhaps tens of meters in size. A type 3 oasis might be related to an intruded basalt body several tens of km in size. This size would be sufficient to keep our nominal temperature difference after a few million years. A dike with a meters scale would preserve it for only a matter of years [Fowler, 1990]. A type 3 oasis could be of any size, depending on its age. A type 2, geyser-like oasis would be much smaller. In our conception of it, a Martian hydrothermal vent would be only a few meters in size, and the area affected by heating would not go very far beyond the lip of the vent. Thus, an individual vent might only display our suggested temperature signature over a few square meters.

The likelihood of heat islands on Mars today is thought to be small. Certainly Mars as a planet has cooled in the last billion or so years since the more recent floods, and the currant average heat flow at the surface is estimated at only 30 mW/m^2 [Schubert *et al.*, 1992].

Table 1
PLANETARY HEAT FLOW

Planet	Heat Flow
Earth	50 mW/m^2
Mars	30 mW/m^2
Io	2 W/m^2

In Table 1, the modeled Martian heat flow is compared to the average heat flow on Io and Earth, both of which we know to be volcanically active. Io likely has an active heat source in the tidal friction provided by Jupiter to explain its globally high heat flow. On the Earth we know that volcanism and increased heat flow sufficient to drive it is associated with lithospheric plate boundaries. Thus, we know that a relatively low average heat flow does not rule out regionally enhanced geothermal activity. In other words, Mars' low heat flow may still not preclude geothermal anomalies; they remain unlikely, but terribly important should they exist.

DETECTION

Detection of extant Martian oases from orbit should be based on the expected properties of these locales. All three types of suggested oasis are related to an increased geothermal heat flow. Such a thermal anomaly would correlate with a density anomaly of the rocks at depth, and so one way to map such regions would be to do a detailed local or regional gravity study. However, the intrinsic resolution of gravity measurements is proportional to the altitude of the sensor, and so an orbital sensor might not produce data with sufficient spatial resolution to unambiguously determine an oasis location. In our discussion we have also asserted that a warm oasis on modern Mars would have associated with it some form of water anomaly. One suggestion for oasis detection has been to seek out an anomalous water signal in atmospheric spectra. This may turn out to be one method that is applied to the problem. However, the signal from an oasis may be very small in comparison to the normal variability of water vapor in the Martian atmosphere due to atmospheric dynamics, photochemistry and cloud physics. We feel that the knowledge is not well-defined enough to permit unambiguous detection of small oases. The principal remotely detectable property of our postulated Martian oases would be their thermal signature.

Remote sensing of the thermal signatures of solid surfaces is a very well-developed technique [Elachi, 1987]. The basis for the technique is Planck's law, which describes the spectral radiant intensity emittance $H(\lambda,T)$ as a function of absolute temperature T and wavelength λ:

$$H(\lambda,T) = c_1\lambda^{-5}[e\,xp(c_2 / \lambda T) - 1]^{-1} \quad (1)$$

where $c_1 = 3.74127 \times 10^{-16}$ W m^2 and $c_2 = 1.4388 \times 10^{-2}$ m K. When the emitted radiation is isotropic, which we will assume here, then $H(\lambda,T)$ is independent of direction, and

$$L(\lambda,T) = H(\lambda,T) / \pi \quad (2)$$

is the spectral radiance. This is what is remotely sensed in a given infrared (IR) wavelength interval, and then converted to an apparent surface temperature after calibration and correction for sky radiance, solar reflection, detector noise and atmospheric attenuation. This does assume however that each resolution element of the detector, or pixel, is viewing an isothermal surface.

To characterize a small oasis unambiguously would therefore require an instrument with pixels small enough to resolve the feature. This is not strictly true however if one merely wants to detect a thermal anomaly; subpixel-sized thermal sources can be investigated. This has been applied on Earth to the study of volcanic events with a view toward monitoring of remote volcanoes [Harris *et al.*, 1995b; Oppenheimer, 1991; Oppenheimer, 1993; Oppenheimer *et al.*, 1993c; Oppenheimer and Rothery, 1991; Rothery *et al.*, 1992; Rothery and Francis, 1990]. Many of these studies have been carried out using Landsat Thematic Mapper near-infrared (IR) bands, with image pixels 50 m in size. Much work has been done showing that not only is technical mastery of the instrument critical [Harris *et al.*, 1995a], but a thorough knowledge of the thermal anomaly's behavior is necessary to make a detailed interpretation [Flynn and Mouginismark, 1994; Flynn and Mouginismark, 1995; Flynn *et al.*, 1993; Flynn *et al.*, 1994; Oppenheimer, 1993; Oppenheimer *et al.*, 1993a; Oppenheimer *et al.*, 1993b].

In the case of Mars, we are not necessarily interested at this point in characterizing thermal anomalies, merely detecting them. Some of the techniques used to detect volcanism on Earth are directly applicable to assessing the detectability of our model types of oases as subpixel-sized features within the Martian background. A pixel that contains two thermal components will have a total radiance R that depends on the fraction f of the pixel that is covered by the hotter surface at temperature T_{hot} within the surrounding T_{back} [Oppenheimer, 1991; Oppenheimer and Rothery, 1991]:

$$R = \epsilon\tau[fL(\lambda,T_{hot}) + (1 - f)L(\lambda,T_{back})] \quad (3).$$

The multiplicative terms ϵ and τ represent the surface emissivity and the atmospheric transmissivity. In Figures 1, 2 and 3, the pixel spectral radiance R is plotted versus f for each of our model oases at selected wavelengths within Martian atmospheric windows. Note that the ordinate scales are different in each Figure. We have assumed a cooler nighttime background temperature T_{back} for the active volcanic and hydrothermal vent types of oasis. For the intrusive thermal anomaly we assume a less favorable configuration of T_{back} = 220 K, only 10 K cooler than the anomaly. In the last case in particular it is clear that the feature must cover a significant portion, if not all of a pixel if it is to be distinguished from the background. An important feature of these plots is the different behaviors of the different wavelengths. This can be used in so-called dual-band calculations; Equation (3) is established for two wavelengths and the system of equations can be solved for f and T_{hot} if T_{back} is known or assumed. Different wavelength combinations might be more optimal for the different types of oasis.

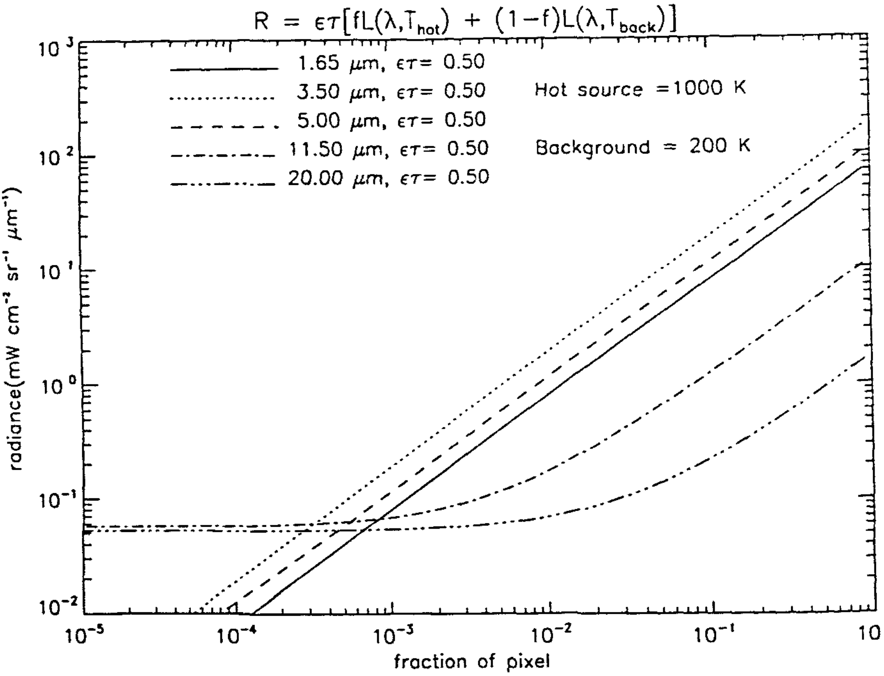

Figure 1 Spectral radiance vs. fraction of pixel for type 1 oasis.

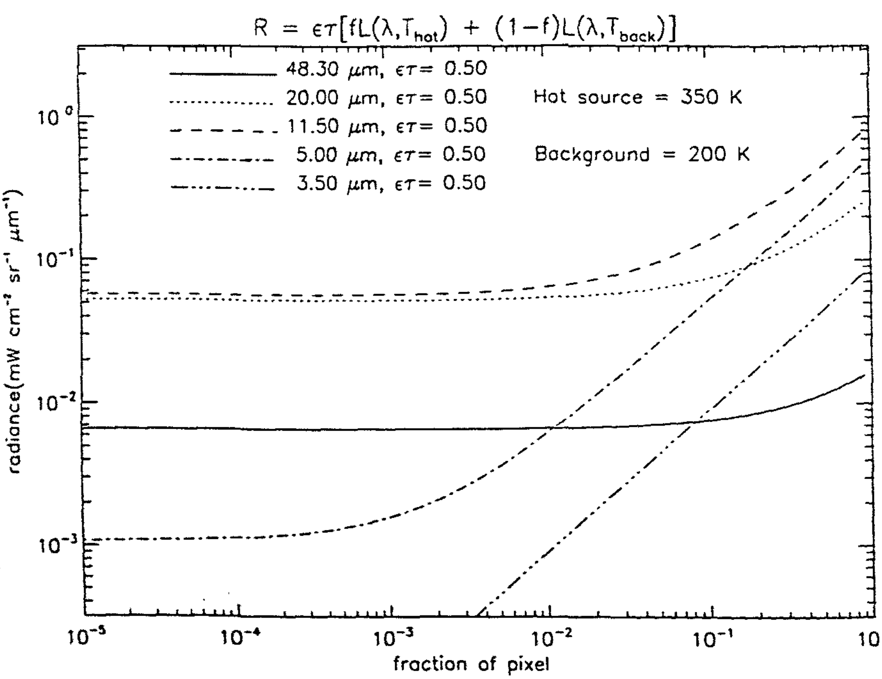

Figure 2 Spectral radiance vs. fraction of pixel for type 2 oasis.

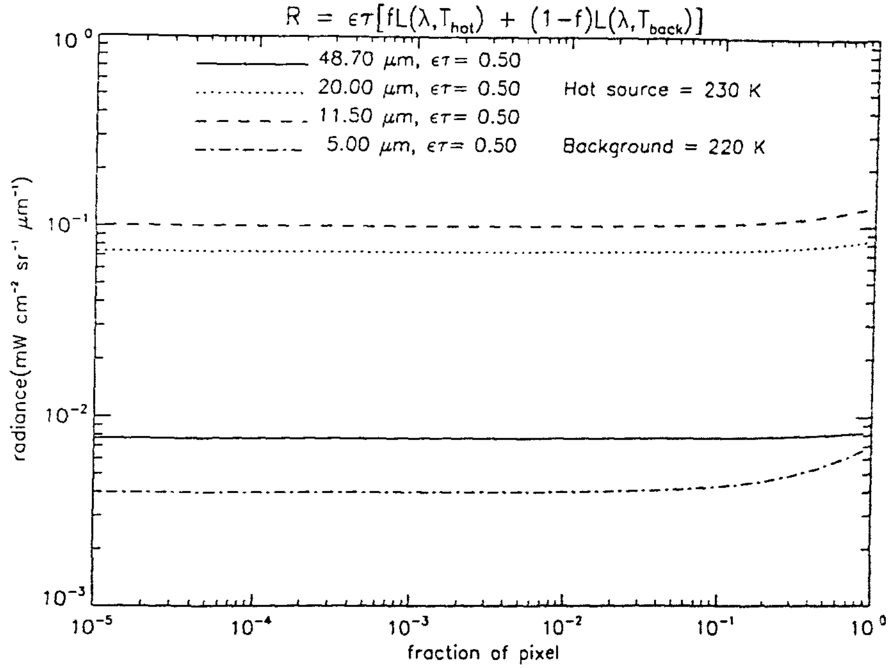

Figure 3 Spectral radiance vs. fraction of pixel for type 3 oasis.

There have already been IR detectors in Mars orbit, and more are planned. We can discuss whether any of these could have detected, or might yet detect, a Martian heat island. If we know the minimum temperature resolution, or noise-equivalent temperature NEΔT that each of these detectors can resolve, then we can determine the smallest f in Equation 3 to which it would be sensitive for each of our model oases. If we take 4 NEΔT above T_{back} to be a significant signal [Kieffer *et al.*, 1977], then we equate the model radiance R from Equation 3 with the apparent radiance $L(\lambda,(T_{back} + 4NE\Delta T))$, and find f_{min}:

$$f_{min} = [L(\lambda,(T_{back} + 4NE\Delta T)) - L(\lambda,T_{back})] \,/\, [L(\lambda,(T_{hot}) - L(\lambda,T_{back})] \qquad (4)$$

The spatial resolutions and spectral properties of various Martian IR detectors are summarized in Table 2. Also shown are the limiting f values for each of the wavelengths and oasis models. Kieffer *et al.* [1977] searched the IRTM 7 μ band and found no evidence for oases; "individual measurements [in the predawn region] with temperature differences of 4 K from adjacent pixels would have been noticed." While the Viking IRTM did not even get close to global coverage at its highest resolution, Kieffer *et al.* [1977] state that their smallest detectable 400-500 K cooled lava lake would have had to be at least 200 m in diameter. This is entirely consistent with our oases. The MGS TES will get global coverage but the detection size limit is only 3 times smaller than for Viking. PMIRR on Surveyor '98 may do much better, particularly in the 6.9 μ and 7.6 μ bands. These bands are not primarily intended for surface sensing and some atmospheric water (6.9 μ) and CO_2 (7.6 μ) opacity will intervene in surface temperature sensing. Nevertheless, the minimum oasis sizes to which PMIRR's short wavelengths are sensitive are closer to what we would want to search for. Unfortunately, PMIRR's surface coverage will not be global, and so PMIRR will not achieve our goal of a global search for oases.

Table 2
MARTIAN THERMAL EMISSION OASIS DETECTION LIMITS

Spacecraft, Instrument	Resolution (km)	λ (μ)	NEΔT (K)	Oasis Type 1: $T_{hot}=1000$ $T_{back}=200$ f_{min}	Oasis Type 1: size (m)	Oasis Type 2: $T_{hot}=350$ $T_{back}=200$ f_{min}	Oasis Type 2: size (m)	Oasis Type 3: $T_{hot}=230$ $T_{back}=220$ f_{min}	Oasis Type 3: size (m)
Viking, IRTM	3 - 60	7	1.0	5.2×10^{-5}	22 - 430	2.8×10^{-3}	159 - 3.2 km	0.36	1.8 km - 36 km
		9	0.5	1.0×10^{-4}	30 - 600	2.7×10^{-3}	156 - 3.1 km	0.18	1.3 km - 25 km
		11	0.3	1.6×10^{-4}	38 - 760	2.5×10^{-3}	150 - 3.0 km	0.11	995 - 19.9 km
		15	1.0	1.4×10^{-3}	112 - 2.2 km	0.013	342 - 6.8 km	0.39	1.9 km - 37 km
		20	0.3	6.8×10^{-4}	78 - 1.6 km	5.3×10^{-3}	218 - 4.4 km	0.12	1.0 km - 21 km
MGS, TES	3	10	0.04	1.4×10^{-5}	11	2.7×10^{-4}	49	0.014	355
Surveyor '98, PMIRR	7x5 (35 km²)	6.9	0.006	5.0×10^{-7}	5	2.0×10^{-5}	26	0.0020	265
		7.6	0.006	2.6×10^{-7}	3	1.4×10^{-5}	22	0.0021	271
		20.5	1	2.4×10^{-3}	290	0.018	794	0.39	3.7 km
		32.6	1	3.7×10^{-3}	360	0.022	878	0.40	3.7 km
		48.3	1	4.3×10^{-3}	388	0.025	935	0.40	3.7 km

IMPLEMENTATION

Our intent is to propose a method of conducting a global survey for Martian oases. Based on the short wavelength performance of PMIRR, we would suggest an imaging detector system with similar sensitivity, probably with a passively cooled focal plane to improve NEΔT [McCleese *et al.*, 1992]. To unambiguously detect type 2 oases, we would want to be unambiguously sensitive to about 0.25 m^2 at 350 K in a nighttime background of 200 K, which would require a surface resolution of 50 m or less if an f_{min} of 10^{-4} can be achieved for an imaging thermal emission detector. With these parameters, while type 1 oases would be clearly detectable, type 3 oases would only have to be 2 m in diameter, which could mean that some confusion would arise from contrasting exposures of bedrock with high thermal inertia within expanses of dust. To mitigate this source of confusion would require only surveying the nighttime portion of the planet where the surface is coldest, just before sunrise. To attain the necessary sensitivity and spatial resolution without huge optics might require active cooling of the detector. New space-ratable Stirling cycle cooling systems may be appropriate [Bradshaw and Orlowska, 1995; Davey and Orlowska, 1987; Orlowska and Bradshaw, 1992; Orlowska and Davey, 1987].

The choice of wavelength will also be important. It appears that the 7 μ range that may provide the best results with PMIRR may also be the most appropriate from the point of view of minimizing Martian atmospheric dust opacity, while maximizing the radiance incident on a detector. Wavelengths much longer than 20 μ will have lower radiances that will be harder to detect, while shorter wavelengths will be more affected by suspended particles in the Martian atmosphere.

At the fine spatial resolution we suggest, transmission to Earth of all the images required to map the whole planet would not be practical, if not impossible. To circumvent this difficulty while still providing global detection coverage requires that essentially all detection processing be carried out on board the spacecraft. This procedure is not unheard of, and would in fact be analogous to modern high energy particle physics experiments where the signature of a detection is predictable, as it is in our case.

We had hoped initially that a system with sufficient spatial resolution might resolve the question of Mars' heat flux. Thus, if no oases were detected, the Martian geophysics community would still be provided with a significant upper limit on current geologic activity on the planet, and the mission investment would still provide a return. As it happens it seems that any thermal anomaly that is buried at significant depth, or is not very recent, will be masked by the heterogeneity of Mars' surface thermal properties.

CONCLUSION

We believe that a single thermal emission detection instrument will be able to determine if there are significant oases or heat islands active on Mars today. The required techniques are already in use for the study of remote volcanoes on Earth, using the Landsat satellite's sensors. The imagers on Landsat are very high resolution when compared to what is currently planned for thermal sensing at Mars. Planned missions to Mars will provide substantial upper limits for the problem, but will not resolve the question. The potential importance of a Martian oasis requires that the question be resolved in a timely manner. An orbiting instrument using current state-of-the-art thermal detection technology should be able to answer the question. Certainly, data relay constraints will require significant onboard data processing, but this should be feasible. More specific technical details of such a high spatial resolution imaging thermal emission detector will need to be addressed by further study.

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