The Road to Mars

A computer modeled analysis of the feasibility of using Large Deployable Reflectors to redirecting solar radiation to the Martian surface.

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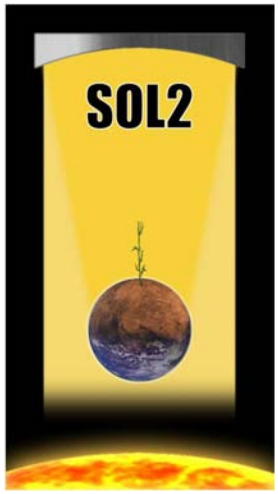


Abstract:

An innovative idea for Mars colonization is the use of large aperture orbital reflectors to heat, localized areas of the Mars surface. Projections show that a network of two to three hundred, 150 meter diameter reflectors in monolith form or a series of small clustered groups would provide roughly the same irradiance as on earth to the Mars surface. The goal of this research is to begin to prove that it is possible to heat the surface of the planet. Both stray light analysis of the atmospheric light propagation and Finite Element Analysis (FEA) will be used to model the materials, radiating thermal transfer, general surface and environment effects that are the key to understand and proving this concept. This research will take a step by step approach to identify and solve the conceptual problems, and cover topics from basic radiometric math to FEA model optimization.

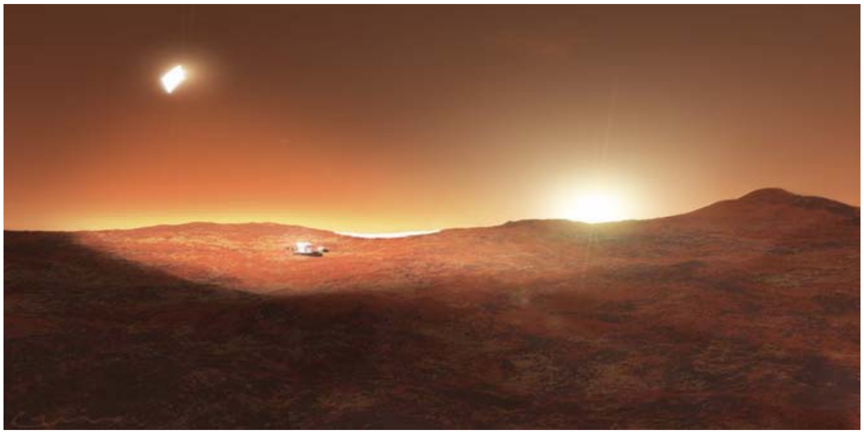


Fig. 1 Shows the surface lighting concept.

1. Background

a) Origins of analysis and project

The project is a joint effort between College of Optical Science (OSC) and NASA Institute for Advance Concepts (NIAC) to look for ideas and technologies that are 10 to 40 years into the future in application. This research is dominated in the idea that in 25 to 30 years a manned mission to Mars will be launched. Do to the adviser weather condition on Mars, it is going to be extremely difficult for the astronauts to function on the Martian surface.

This project aims to begin to answer the question of whether it is possible to modify a small area of the Martian surface, to closely match our own terrain surface. The end goal is to understand the effects of ether putting a 2 to 3 kilometer reflector in geosynchronous orbit of Mars or a series of small clustered reflector in an elliptical orbit. The result of which being an ability to track light propagation through ASAP stray light analysis and FEA modeling of the surface thermal properties, caused by the reflector.

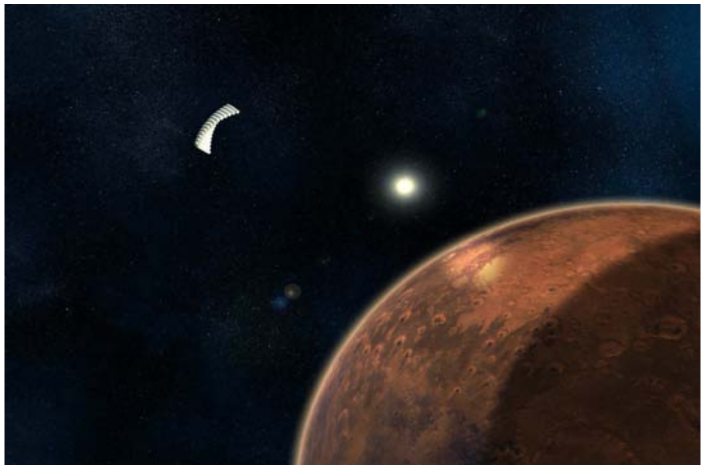


Fig. 2 Orbital single element reflector concept.

Convex array:

The idea behind the convex reflector is the use of several hundred 150 meter diameter convex segments. This would deliver the same energy as the concave collector but in a different way. The angle of subtends of the sun would be change to deliver the energy from each reflector to the entire 1 kilometer area. The power of the convex reflectors would increase the angular magnification by a factor of 22. The alignment of this system would be much more forgiving and the lost of any one segment would be insignificant.

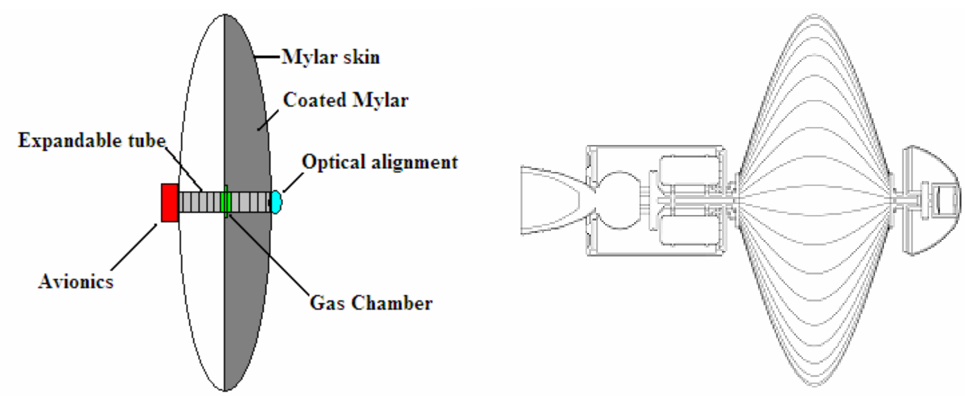


Fig. 3 Basic design of a signal reflector component (left) and final design concept (right).

Each of the 2 to 3 hundred reflectors would diverge the energy collect over the 150 meter area, to the whole 1 kilometer area. This would have the effect of overlapping several hundred intensity patterns atop each other to produce the desired energy needed to heat the surface.

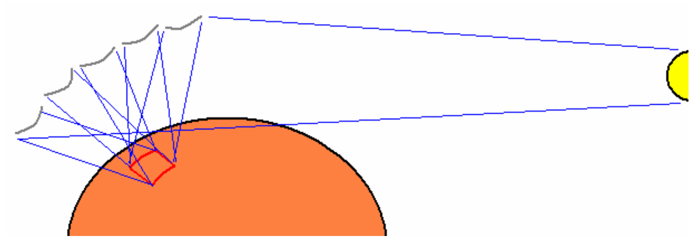


Fig. 4 Shows reflector array working together to collect sunlight from over 150 reflectors.

2. Basic FEA

a) FEA of a simulate ground patch

A critical part of proving that the radiant energy will be absorb, will be conducted by Finite Element Analysis (FEA). Through FEA model we will be able to prove that the Mars will hold the heat from the global reflector. The preliminary model in figure 10, shows basic proof that the surface will begin the heat give enough time. The model takes a block of material with roughly the same properties as the surface of Mars. With a 1.5 x 1.5 x .1 km block in place, the bottom and edges are cooled to – 60 C. This cooling will simulate the active cooling that would take place by ground thermal conductivity. Two radiant sources are now place on the top surface to simulate the sun's energy and the reflectors energy. These sources will be pulse on and off in 12 hours intervals to narrow down the planetary rotation. Finally the model was run continuously in order to see the amount of the time need in order to bring the 1 km area to an Earth ambient level.

The results of the basic FEA modeling shown below on a Mars representative surface plate of 1.5 x 1.5 x 0.1 kilometer, show a gain term of +10 C per every 12 hours of exposure to 1000 W/m^2.

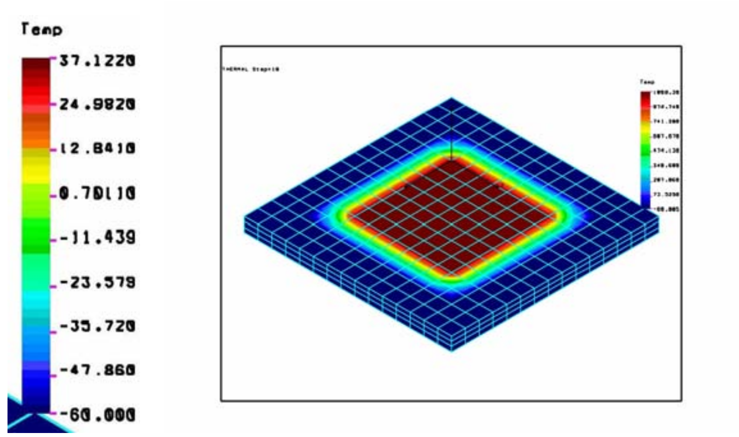


Fig. 5 Shows the modeling of a Mars plate started at -60^{0}C and transitioned to 37^{o}C after exposure.

3. Programming

a) Software

There are 7 sections of the ASAP code that models the Mars atmospheric system, each of which controls a separate variable:

1. Model breakdown
    a. This is the breakdown of values needed to represent coefficient and constants
    b. Material properties like the index of refraction of various gasses and the reflective emissivity of the ground.
    c. Scattering coefficients like the Mie and Rayleigh will be used to model how light is deflected or redirect away from it goal.
    d. Fresnel coefficients will be used to represent the transmission, reflection and absorption effects of the redirected energy through the various layers of the atmosphere.
    e. The physical geometry of the setup will be placing an orbiting object several hundred to several thousand kilometer away from a series of boundary layers and finally a solid spherical mass representing Mars.
    f. The flux source or the sun will be modeled, but only as a intensity profile hitting the orbital reflector. This mean that the model will not include the sun itself, rather small amount of energy that hits the reflector in orbit will be the origin point for the energy traveling through the system
    g. The model code itself will be setup to automatically take and display curtain types of analyzed plot and chart. This will give a fast and easy reference point to observe changes from while refining the as the last step of the project.

4. Generation of models

A straight forward propagation of solar energy will be used, when traveling through open space it is simple to calculate the intensity fall off in power, as we travel to Mars orbit. The Sun can be treated as a relatively Lambertian source and a radiometric configuration factor will be used for the final intensity.

A) Basic Radiometric calculations

$$\Phi = LA\Omega$$

Equation 1. States the basic law of radiometric transfer

$$_{1-2}\Phi = L\int_{A1}\int_{A2}\frac{\cos(_1\theta)\cos(_2\theta)}{d^2}dA_1A_2$$

Equation 2. Is the integration summation of irradiance propagation

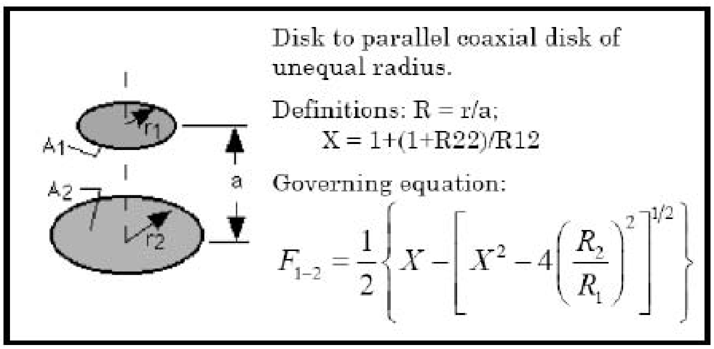


Fig. 6 Shows the short hand Configuration Factor (CF) for the radiometer transfer of energy from the sun to Mar surface.

B) ASAP MODEL

There will be two forms of the ASAP model, a fundamental model and a dynamic model. The fundamental model will be a simplified version of the setup needed to propagate the reflect sun light. The dynamic model will have an increase level of detail over the fundamental model, by incorporating individual reflector components, Mie/Rayleigh scattering, absorption, transmission, and reflection coefficients.

In the pursuit of accurately providing modeling to prove the conceptual base of this proposal, the key feature is a multi-layer atmosphere. The model includes an incident radiant flux that will be redirect and passed through the multi-layer atmospheric layers.

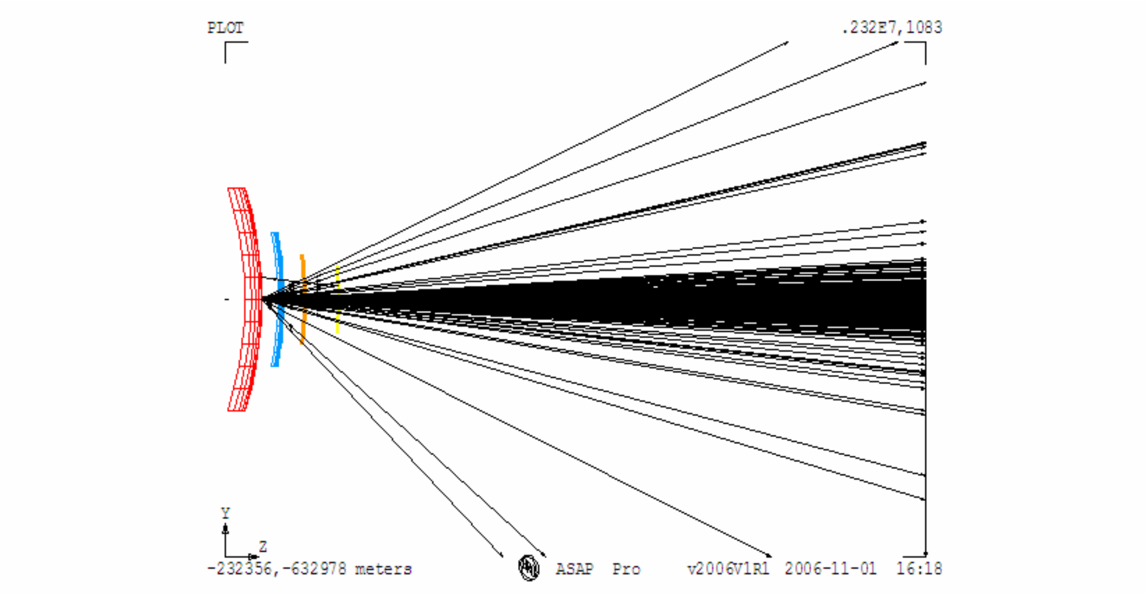


Fig. 7 Shows the overall 2D layout of the fundamental model.

Shown below is the multi-layer setup that will model the light passing through several layers of dynamic atmosphere, then arising incident upon the Mars surface. The model is setup to have a each layer of the atmosphere have a given roughness, transmission, reflection and absorption. In between the layers shown in yellow orange and blue, will be a emissive material that will represent the gas volume, Mie and Rayleigh scattering characteristics. The black lines shown in the plot are the scattered light that is deviated from the direct path to the ground.

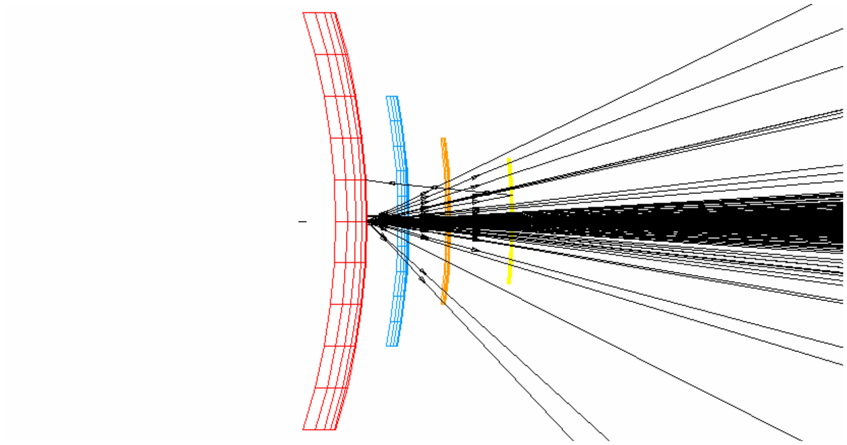


Fig. 8 Shows a close up of the 2D plot, 3 layer atmospheric and ground model.

The figure below shows the whole model after the ray tracing was completed. The 3D plot shows a complete overview of the system, over a 6400 kilometer range. The thin white line traveling from left to right is the direct relay of the solar radiation to the ground.

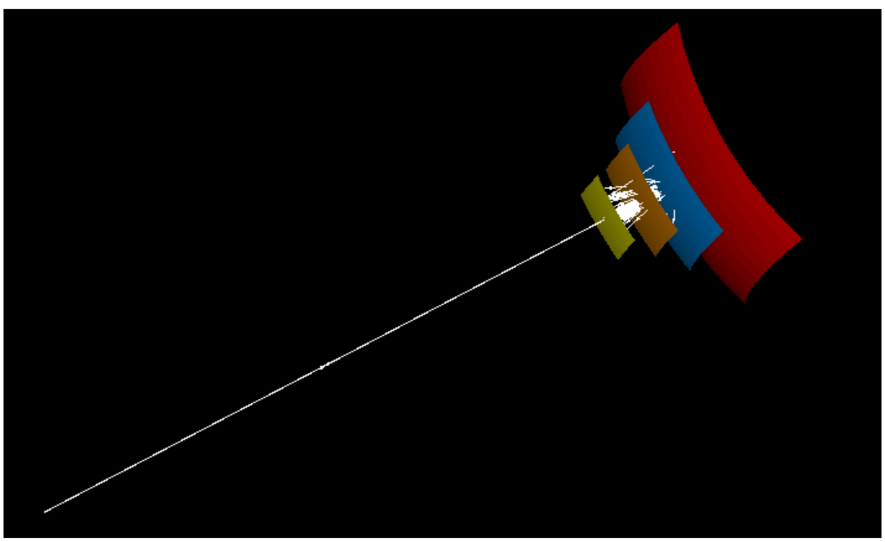


Fig. 9 Shows the whole 3D model of the global reflector propagating light through the atmospheric layers and to the Mars ground.

The plot below shows the light being deviated from the direct path to the ground and scattering over a much larger area. The ASAP software shows the light that has been reflected into the various layer of the atmosphere and loss.

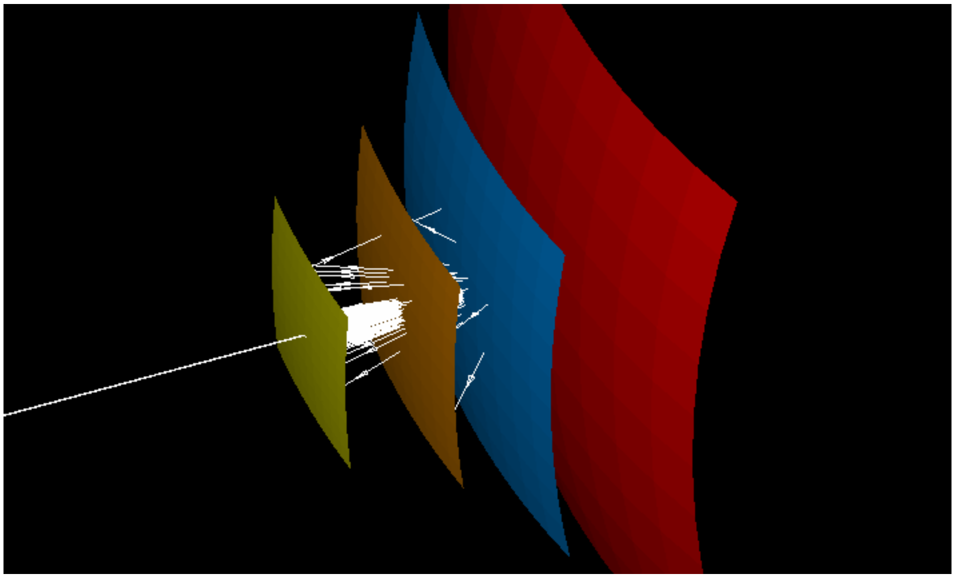


Fig. 10 Shows the relayed LDR light passing through the different layers and plots the light scattering for the transitions.

The figure below show the solar radiation traced from before the LDR, to the monolithic LDR and relayed down to the Mars surface. For this model a singular monolithic reflector was used simplify verification.

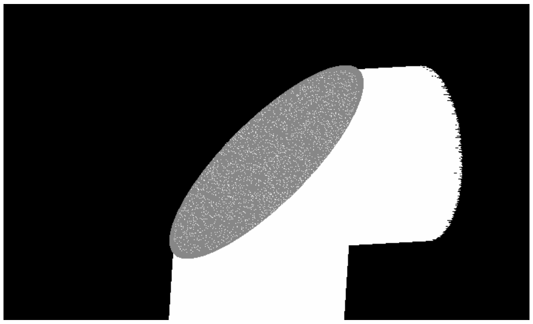


Fig. 11 Shows the monolithic reflector used in the fundamental ASAP model, to relay incident light to the surface.

The plot below shows the contouring variations in intensity over the near area of the on-axis beam. From the plot it is easy to determine the geometry of the energy making it to the ground on Mars.

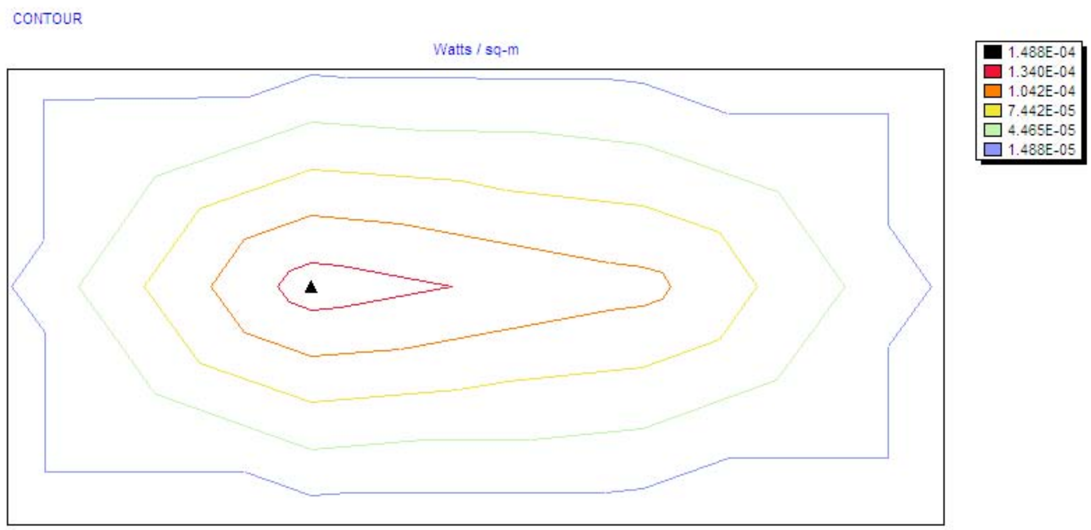


Fig. 12 Shows the localized radiant intensity plot of the relayed light through the atmosphere and to the Mars surface.

In figure 12 the intensity verse the deviation angle off axis is plotted to show the fall off in energy as we move away from the direct beam. What we can see at this point is that the energy is uniform over 5^o on-axis and quickly drops to negligible within another 20^o spread.

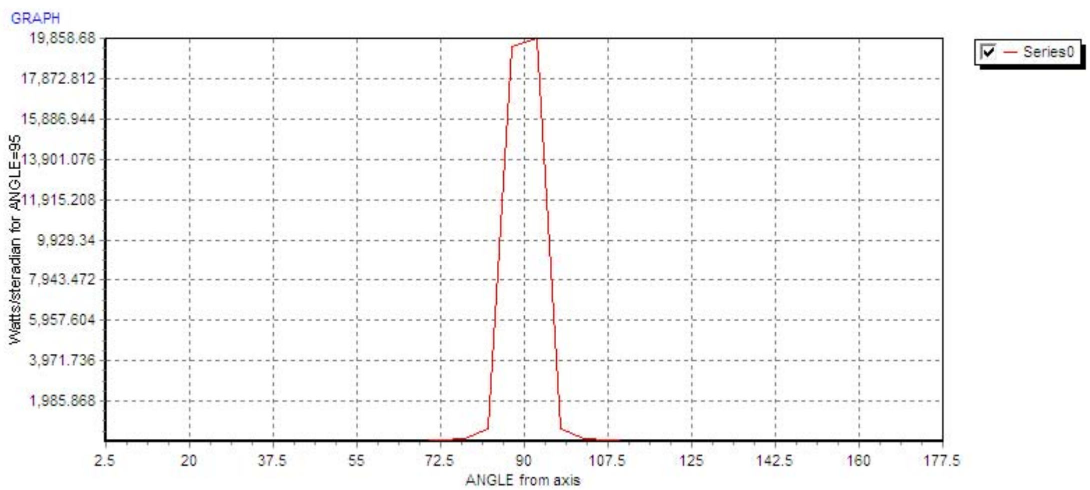


Fig. 13 Shows a plot of the intensity as a function of angle, when you go off axis from the reflector.

In figure 13 the intensity verse the deviation angle in both X and Y is plotted to show the fall off in energy as we move away from the direct beam, giving more detail then before.

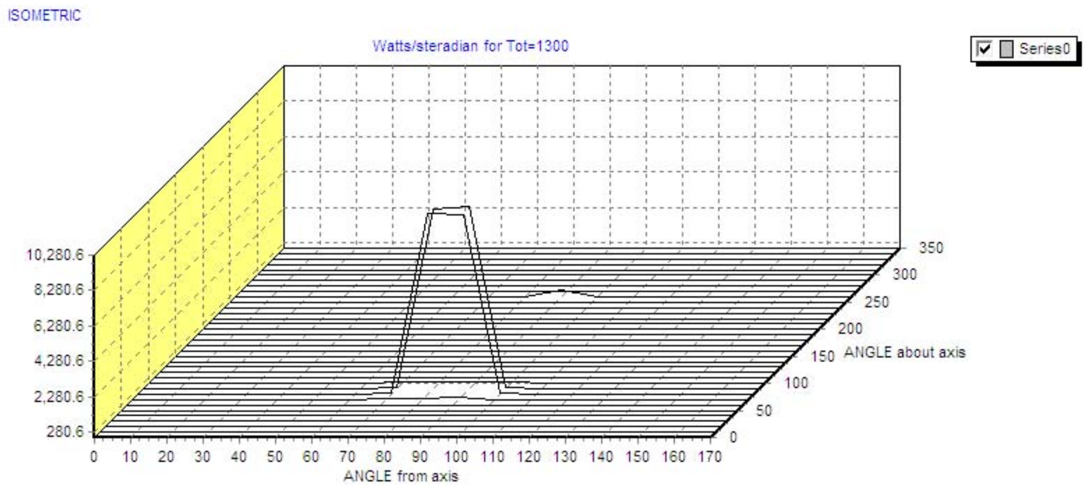


Fig. 14 Shows a plot of the general intensity verse angle in both X and Y axis's.

Once the ray tracing is completed in ASAP some where on the order of 10,000 to 10,000,000 rays. It is a simple matter to back trace the paths of the rays to find out where the final designation of the energy was. ASAP can breakdown the results of the source transitioning through the entire system and shows where the divided energy ends, as seen in table I.

Table I Breakdown of Ray Propagation through the Various Material Layers

Objects	Rays	Flux
REFLECTOR	821	14.99670
GROUND	65150	1190.055
SURFACE 1	13	0.2374629
SURFACE 2	45	0.8219871
SURFACE 3	5140	93.88919
Total	71169	1300.000

The figures below show the generated intensity plots, showing where the final energy ended up. Do to the scattering effects of the atmosphere and Martian surface a percentage amount of the incoming light will diffuse over a large area than projected by the global reflector.

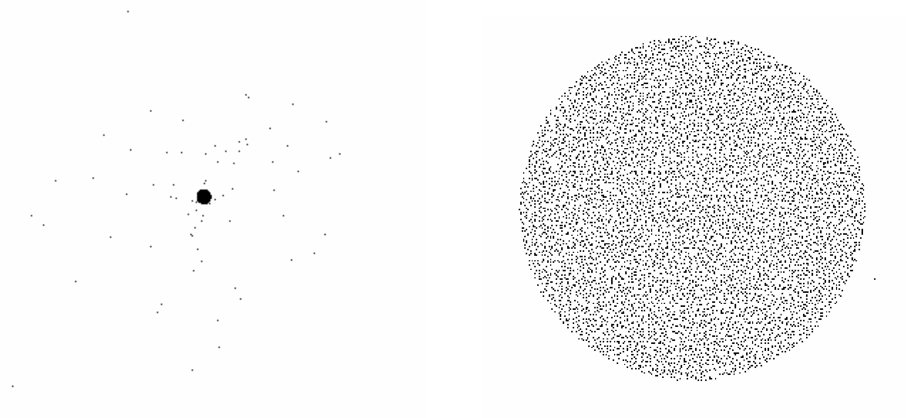


Fig. 15 Plots of a spot diagram over the whole field (left) and over a 3 kilometer squared area (right).

One of the excellent features of ASAP is it ability to plot over a 4pie area, where the energy of a system is traveling to.

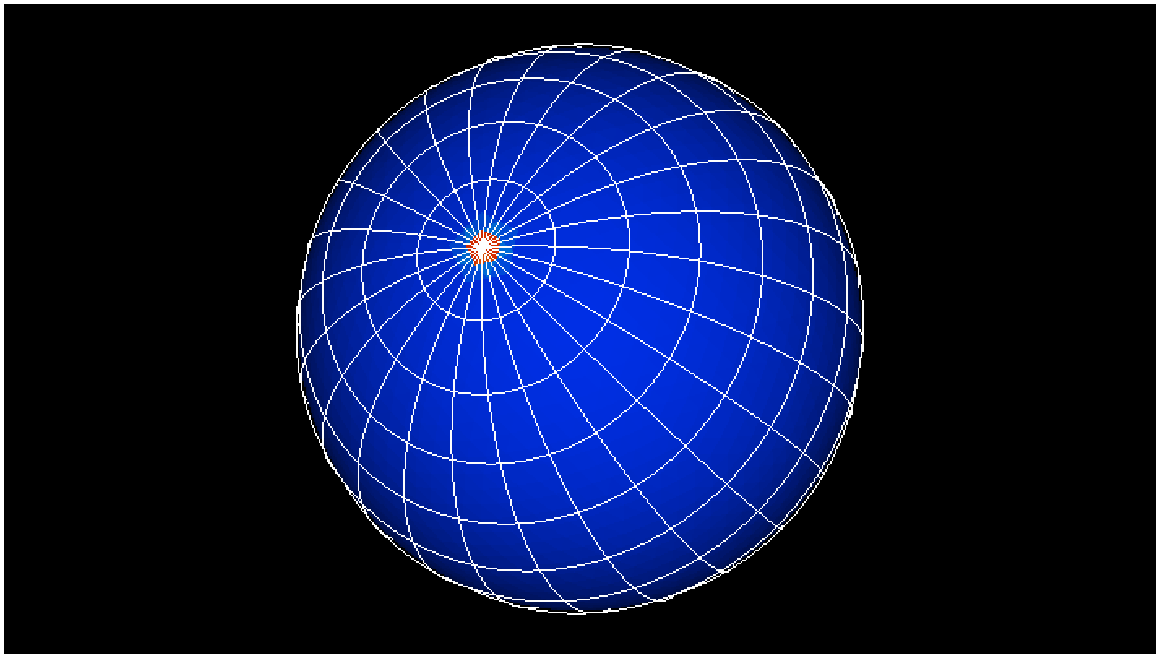


Fig. 16 Show the radiant flux as a function of steraden sphere.

The figure below shows the breakdown of the intensity distribution over a directional sphere. The advantage of this kind of plotting ability is in the tracking of the irradiance come out of the system.

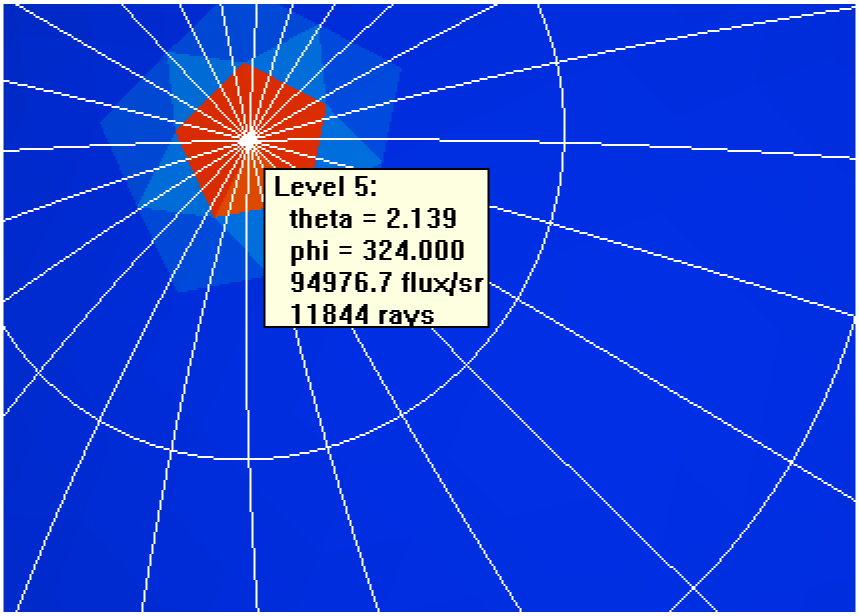


Fig. 17 Shows the different intensity levels on the radiant sphere.

C) Environment Properties

Atmospheric layering:

The atmospheric layering of Mars is made up of three primary layers, so too will be the representative layers in the ASAP modeling. The three layer are made up of various sizes, density, pressures and gases, all of which can be accounted for in ASAP..[1]

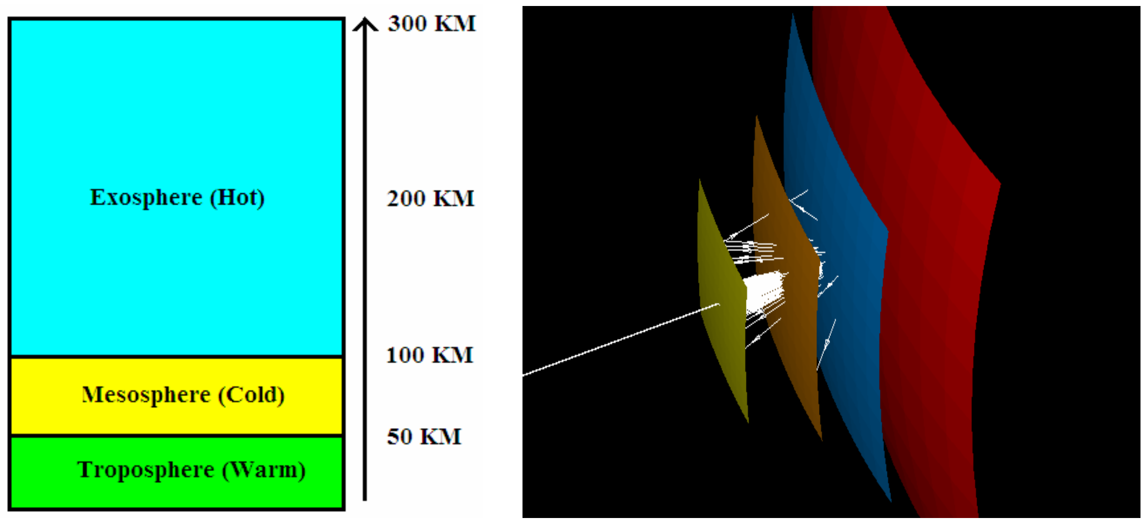


Fig. 18 Shows the atmospheric layering that will be used for a representative Mars (left) and the layers themselves in the ASAP model.

Where as on Earth the atmosphere is made up of (78%) nitrogen and (21%) oxygen, the Mars atmosphere has (95.3%) CO_2, (2.7%) nitrogen, (1.6%) argon, (0.15%) oxygen, (0.03%) water vapor and some methane the key is to find the different concentrations in the layers. Along with the gas content in the atmosphere a key part of being able to accurately model the light penetration onto the Martian surface, is the correct tracking of the dust and particle in the layers.[2,3,4]

Table II Shows a breakdown of the elements of Mars atmosphere[2,3,4]

Layer	Altitude (KM)	Temperature (K)	Pressure (bar)	Content
Troposphere	0	250	0.006	Dust
Mesosphere	50	150	10^{-5}	Water-ice
Stratosphere	100	75	10^{-6}	CO_2 clouds
Exosphere	200	250	$>10^{-6}$	None

Dust and Clouds:

This section of the ASAP modeling will be the most difficult the representatively created and will be one of two critical items that will prove or disprove the feasibility of the LDR proposal. A true-colour image shown in Fig. 19 was taken by NASA's Pathfinder and verified by SPICAM spectrometer on board ESA's Mars Express spacecraft, have revealed for the first time that carbon dioxide clouds form and exist at very high atmospheric layers, between 80 and 100 kilo meters above the Martian surface

Fig. 19 Shows a picture of 80 to 100 kilometer high carbon dioxide clouds.

Shown in Fig. 20 is the basic idea behind why the surface of Mars is not freezing, but rather has a somewhere temperate climate.[1]

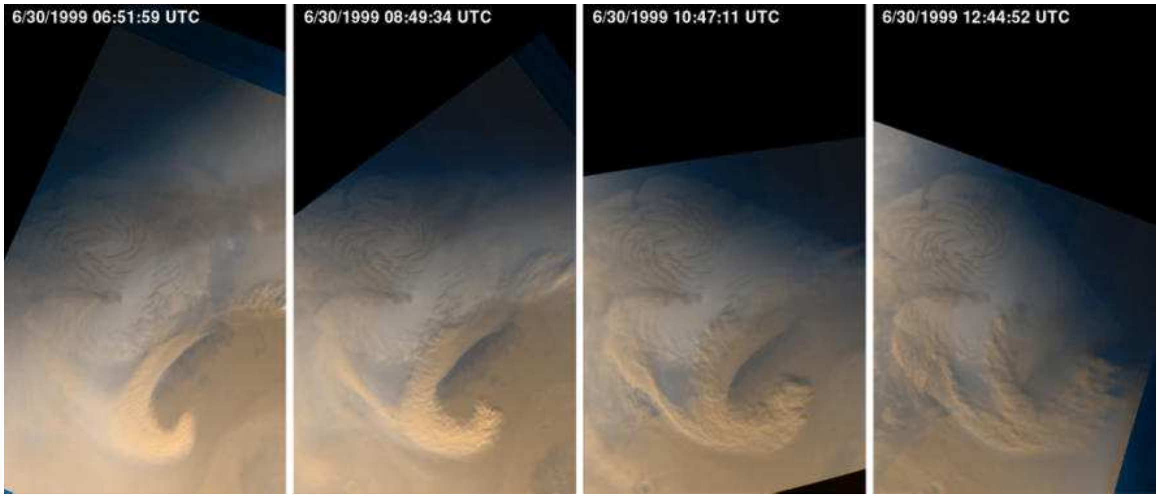


Fig. 20 Shows the propagation of Martian dust storms changing the amount of light that is blocked from the surface.

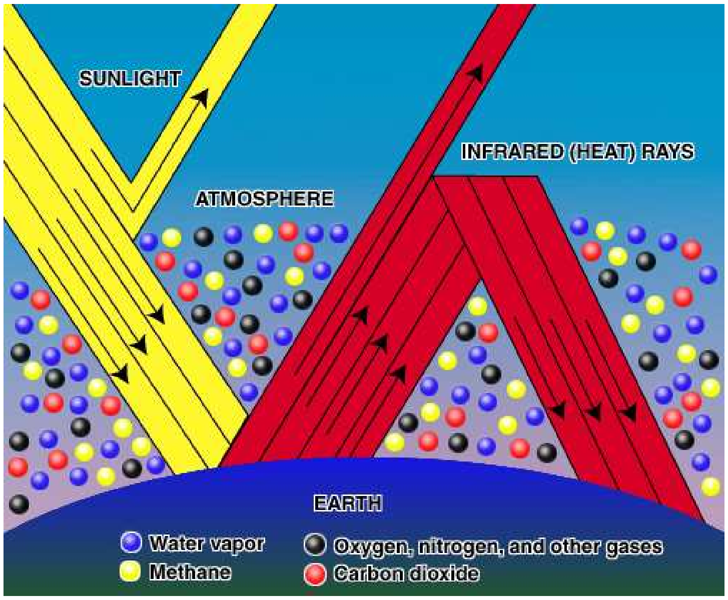


Fig. 21 Shows the green house effect of light being absorb, reflected and transmitted into and through an atmosphere.[1]

This section has the greatest advantage to the idea of use several small clusters of reflectors in a high elliptical polar orbit (HEPO) and has a disadvantage to the geostationary monolithic design, both of which will be discussed later in the paper.

The advantage to the HEPO lies in that distance that the reflector will be from the ground and what part of the atmosphere it sees. The HEPO cluster would travel extremely close to the ground at an altitude of about 200 to 400 kilometer. This would allow the reflector heating to take more advantage of the greenhouse effect, trapping energy inside the thermal atmospheric layer of Mars. Where as the monolithic reflector would be located approximately 7000 kilometer away and would be punching through the thermal layer rather than riding along the edge of it.

Specific Material Parameters

The multiple layer of the atmosphere requires not only understand of the geometer and orbital dynamic but also the index of reflection, Rayleigh and Mie material properties that will effect the propagation of the reflected energy through the atmosphere to the ground.

The ground material itself also poses a challenge in the correct modeling of the scatter, absorption and reflection coefficient that will retain or reject the income radiation.

$$\delta_{total} = \delta_{scatter} + \delta_{absorption}$$
$$\delta_{scatter} = \delta_{molec} + \delta_{aerosol}$$
$$\delta_{absorption} = \delta_{H_2O} + \delta_{O_3} + \delta_{CO_2} + \ldots\ldots\ldots$$

Equations 3. Shows the progression of the energy disrupting effects that prevent propagation of the reflected energy.[5]

$$\delta_{aerosol}(\lambda) = \delta_{molec}(\lambda o)(\lambda o / \lambda)^{4}$$

Equations 4. Shows how to calculate scattering effect at a given wavelength for both Rayleigh and Mie.[5]

$$\delta_{molec}(P) = \delta_{molec}(Po)(P / Po)$$

Equation. 5 Gives us a relationship between pressure and the Rayleigh scattering.[5]

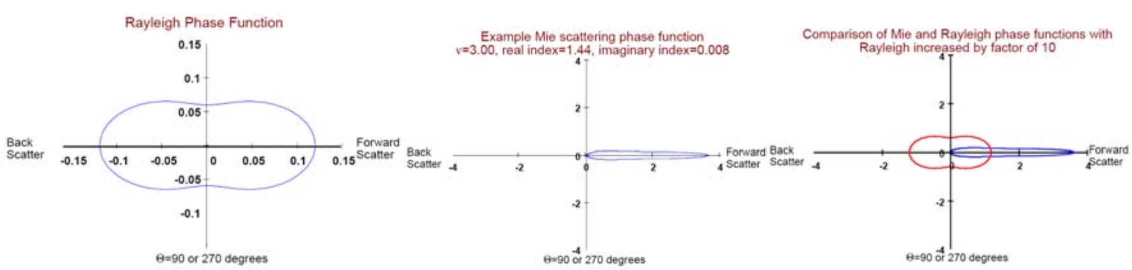
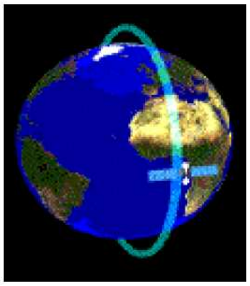


Fig. 22 Shows the phase change of the light as is passes through particles and is scattered[5]

D) Orbital Path

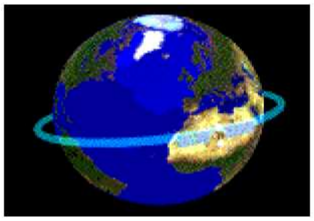
There are several different orbital paths that can be used in order to reflect the incoming light onto the ground.

Polar:



The use of a Highly Elliptical Polar Orbit (HEPO) similar to what is being used on the Mars Reconnaissance Orbiter will have several advantages and disadvantages. From a mission risk point of view the HEPO idea to the one to go with, it will allow for greater diversity in controlling the heating the planets surface. Because of the advantages of the HEPO system we could bring the reflectors in as close a 150 kilometer without a problem, increase the energy delivered and decreasing the amount of loss do to path deviations. A HEPO system would require the used of multiple clusters of reflectors to give the same coverage as the monolithic reflector system. Each cluster would only have about 8 to 10 minutes per orbital cycle to redirect energy to the surface, but it would be able to cycle upper wards of 10 times a day. This would require 7 cluster to get the same time coverage as the monolith, but requiring only twenty of the 150 meter reflectors. With 7 clusters at 24 reflectors per cluster a total of 168 reflectors would redirect the same amount of energy as the 200 reflector monolith 7000 kilometer away. Also because of the HEPO orbital dynamics it is easy to change the path the reflectors would take to swath across the target area, allow some amount of weather adaptation to be possible.

Equatorial Geostationary:



The use of a geostationary large scale reflector would provide a fairly continuous path of energy for at lease 12 hours of the almost 25 hour Martian day.

E) Description of Finite Element Analysis model

The FEA model is an extremely powerful modeling tool that can be used to sub-globally analyze what the energy being redirected is doing as a planetary system over not just the 1.5 kilometer area we want to heat, but how that energy is diffused throughout the affected areas. The goal of heating a 1.5 kilometer area really is finding the amount of time and energy it will take to find a thermal equilibrium with the connecting areas. The energy that is sent into the ground will be diffused out to an unknown distance in all three directions. The idea is that the ASAP model will take into account what happens to the energy that does not make it in to the ground and the FEA model will take into account what happens to the energy once it makes it into the ground and diffused into roughly an $2\pi\Theta$ area.

F) Absorption Materials

One of the main keys to proving whether a planet can be remote heated by use of a set of external reflectors is the tracking and predicting of how surface materials absorb energy. Once the energy is collected and transmitted, it is traced to see how much makes it through the atmosphere from either design of the two proposed reflectors. We still have to discover what happens to the energy that makes it to the surface or below. The hardest element of this project to simulate is whether redirected sunlight will heat the surface of the planet or whether it will simply reemitted into the atmosphere and lost to space. The planet Mars and its absorption characteristics falls somewhere between the two extremes of Earth and the Moon. For example, the planet Earth absorbs and traps a large enough amount of the incoming energy that the planet stays warm. The extreme contrast is a body like the Moon where in direct sunlight the heating is large and in shadow there is no retention of the energy and it is quickly lost radiating to space.

Part the solution can be modeled in FEA where the material reflection and emissivity are track for a certain amount of energy incident upon the surface. However the model falls short on telling you whether the material works over a broader range of the spectrum and in all three dimensions through the ground and into the atmosphere.

Using data from orbital platforms and ground sensors we can obtain an average emissivity for the characteristic solar spectrum and from that determine our calculation in FEA to acquire an answer on the energy propagation and absorption. However this does not represent the total model which would take into account emissivity changes as a function of wavelength and the ground penetration effect.

Results taken from instrument like Mini-TES on the Mars Exploration Rovers (MER) and Mars Global Surveyor's Thermal Emission Spectrometer (TES) instrument, will allow for the average material characteristics to be derived.

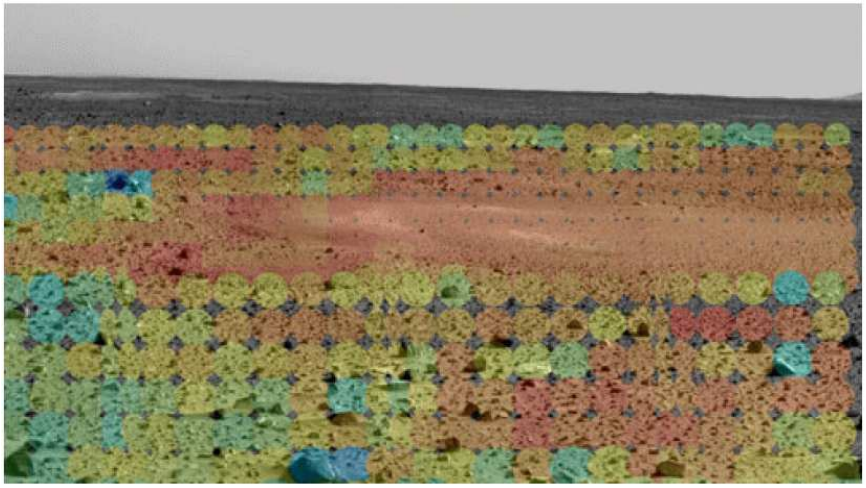


Fig. 23 Shows an image taken by MER rover of the change in emissivity.

The second problem with this modeling technique is that the emission of the ground will not be taken into account by the FEA model. To best address this challenge, instead of only a calculation on how much of the energy is being absorbed, how much the ground temperature is raised, and then how much is radiated back to space, this model would be tied together by comparing the calculation with laboratory sample measurement and verification, which is beyond the scope of this project.

In figures 24 and 25 we see how the spectrum from the sun is not a clean uniform energy signal or spectrum, but rather a complicated plot of varying strengths. The optimal solution to this modeling problem would be to measure directly a hyperspectral image of the Mars surface both in Sun light and at night. This would allow for data analysis on the absorption and emission characteristics of the Mars material present on the surface, thereby completing our picture of energy input verse direct loss.

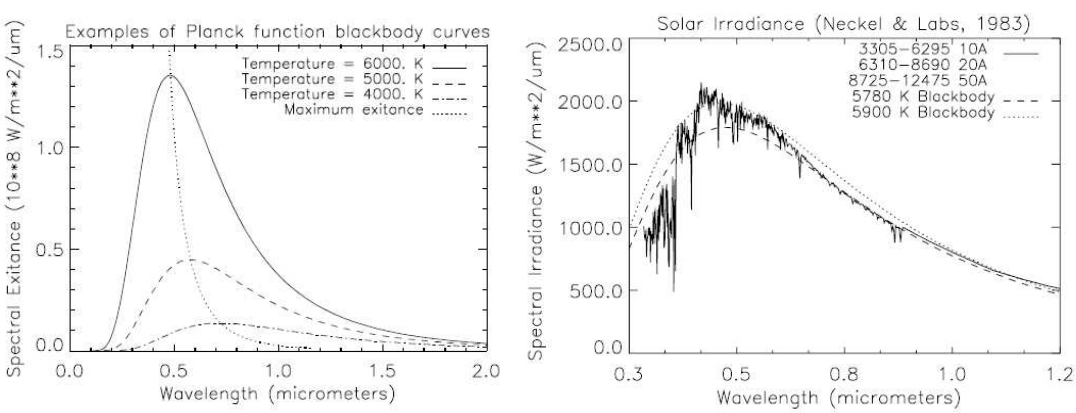


Fig. 24 Shows the Planck's blackbody curve and measured spectra irradiance coming form the sun[6]

Stefan Boltzman Law - $M=\sigma T^4$ [W/m^2] Where $\sigma=5.67\times10^{-8}$ [W/(m^{2}T^4)]

Equation 6. States the energy output of an object based on it temperature.

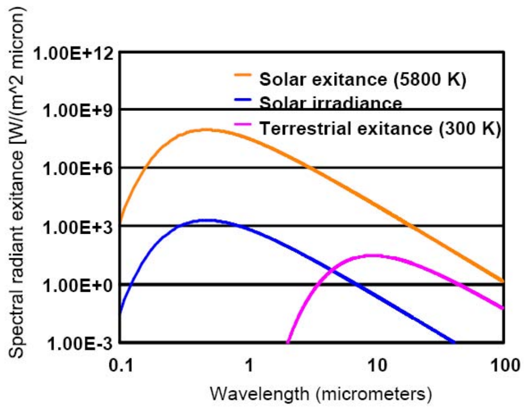


Fig. 25 Shows an example of spectral exitance curved at the sun, at the earth atmosphere and once the energy makes its way through the atmosphere. [6]

5. Final LDR Concept

The final concept for the LDR was generated to be a series of separate units that would individual travel to Mars and deploy into an array of reflective mirrors. In the figure below is the outline concept for using an inflatable Mylar balloon system to produce the LDR segments.

Fig. 26 Shows the LDR package approaching Mars (left), deploying (center) and fall into HEPO orbit fully deployed (right).

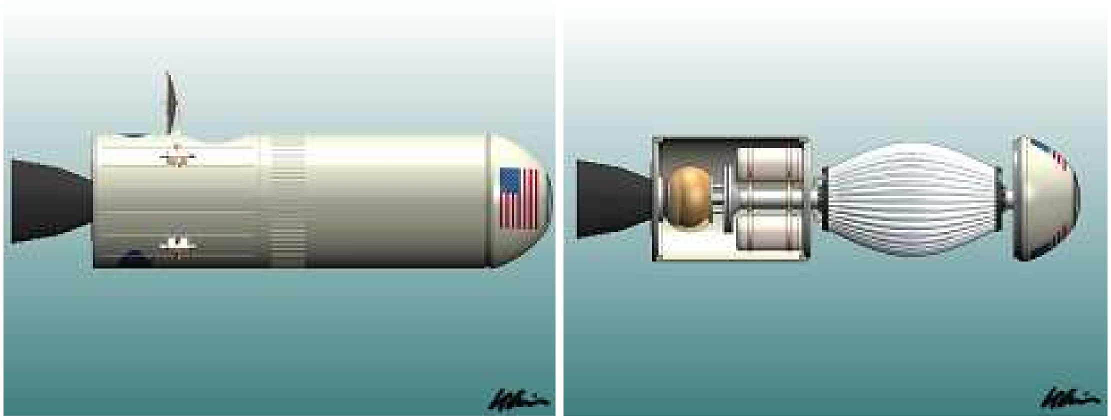


Fig. 27 Shows the LDR package (left) and internal components (right).

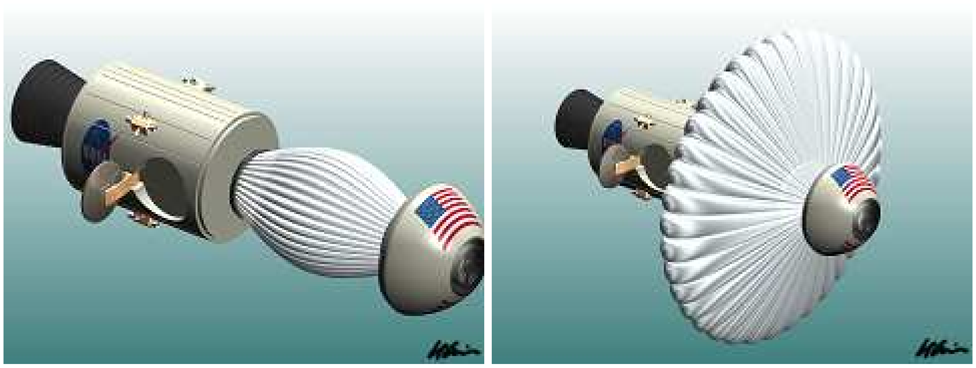


Fig. 28 Deploying LDR package.

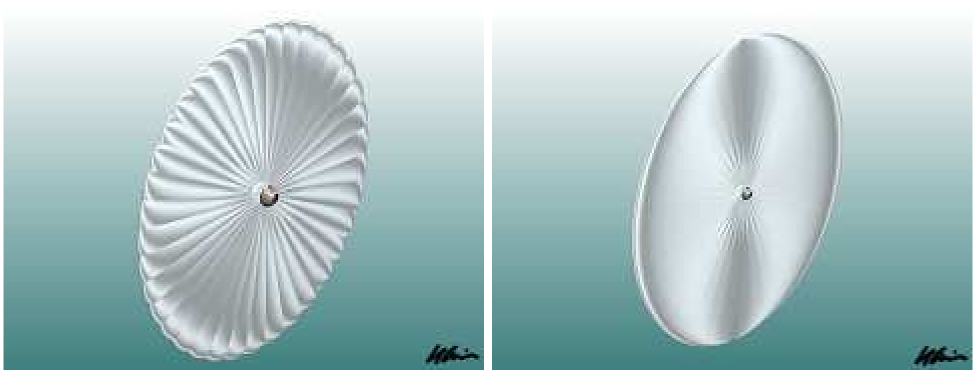


Fig. 29 Deployed LDR.

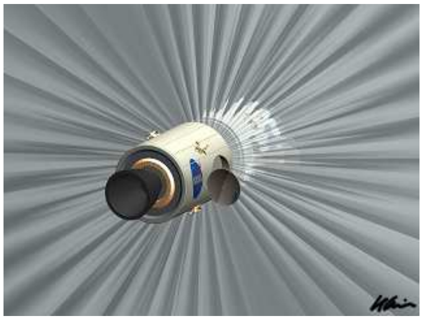


Fig. 30 Shows navigation components with deployed LDR.

6. Future Work

a) Surface Characterization

A characterization of the surface of Mars is needed in order to accurately model both the energy transfer into the surface of Mars and the energy escaping back into the atmosphere or space. The characterization would consist of two major parts; the emissivity of the ground soil and the spectral profile that is absorbed. From these two quantities we will be able to correctly breakdown the surface heating model to raw irradiance coming in, absorbed and reflected. This would be used to modify the energy profile radiating through the atmosphere to the ground and finally allow for the calculation of the total energy making it into the ground.

b) FEA Model

The FEA could be used as the Rosetta stone in the proof of concept; it would show whether the concept has a positive thermal gain over the life cycle of the mission. The FEA would allow for complete modeling of the final energy absorbed into the ground and its diffusion into the Mars terrestrial area in 3 dimensions. The key to completing this model is the accurate representation of an energy source that varies over time as the reflector flies by, is active periodically and thermal conducts into the planet. This would prove whether an over head orbital reflector could ever produce a positive thermal increase in the inherently cold environment, a least over a small amount of the Mars surface. Once modeling was complete, the thermal gain information would finally be used to redesign the initial reflector size and orbital paths, to optimize the LDR performance.

7. Conclusion

There are several final conclusions that can be made base on the analysis that was completed, research into current Mars mission and satellite orbital mechanics. The first is that a large amount of the energy from a global reflector would easily transit through Martian atmosphere to the ground, based on the model shown in figure 9. The results being a loss of only ~9% of the energy from bouncing or scattering off the internal atmospheric layers, shown in Table I.

The second conclusion is that a large geostationary reflector is not the best solution as was originally proposed. Instead a series of smaller reflectors with a tighter orbital path is the solution. The original concept laid out a monolithic reflector in high orbit that would scan through, redirect sun light onto the Mars surface. This design was also based upon the first hand assumption that the sun could be modeled as a plan wave source of energy and had no angular subtent. The final design takes into account the reality of the solar constraints and proposes a smaller set of closer flying reflectors, rather than a massive monolithic reflector at 6000 kilometer orbit.

The proposed final reflectors would be designed to be used in a Highly Elliptical Polar Orbit or HEPO. The HEPO design takes a series of 6 to 12 reflectors that would fly at an average height of 100 to 300 kilometers above the Mars surface, as opposed to the 6000 kilometer monolith. This redesign has the effect of dramatically increase the energy flux that is transfer through atmosphere per unit area of the reflector. Because the sun is not an ideal point source the $L=1/R^2$ effects of the two designs come heavily into play and in the end the HEPO design is at least 200 times more efficient at delivering energy to the surface of Mars. An added benefit of reducing the distance between the HEPO reflectors and the ground is a decrease in scattered energy transitioning through the Mars atmosphere. However the HEPO reflectors would fly through the largest concentration of the Mars atmosphere during its orbiting and therefore there will not be a large increase in throughput do to addition atmospheric skew on the incoming light.

The HEPO design has a large advantage in adaptability over the monolith design, do to the highly elliptical polar orbit characteristics of the LDR's flight path. A HEPO orbit allows for easy and low fuel consumption adjustment to be made to the flight path at the far end of its orbit, several times a day if necessary. This would allow for flexibility in controlling the surface heating as well as allowing for environmental conditions adaptation, where the orbital path could be adjust in response to a dust or stormy weather over the target area.

The final advantage of the HEPO design over the monolith is the decrease in size of the reflector. The angular subtent of the sun is one of the biggest variables in the final sizing of the LDR reflector, if the goal is to cover the 1.5 kilometer square area of the ground. Relaying the solar imprint of the sun over the target area is significantly small with a HEPO design, because the HEPO's orbit path is so much closer to the surface. The low flying HEPO reflectors would require 1/5 the square area or a reflector 22 times smaller to cover the full 1.5 kilometer square area then a monolith design. However as part of the HEPO design, multiple reflectors would need to be used to give a continuous flux to the surface. Here in lies the only drawback of the HEPO design, a highly elliptical orbit has a fairly fast scan rate over the ground and would require up to 12 reflectors to give continuous coverage night and day. With that taken into account the HEPO would still require half the surface area of the monolith. If we also assume that we only want the reflector working half the day cycle, which the monolith would be limited to. The HEPO design would require only ¼ the surface area of the monolith to achieve the same goals, with far more flexibility, built in backup reflectors and the mission assurance of not having a single point failure for risk mitigation.

The final conclusion of this paper is that the engineering requirements needed to complete the heating of a small portion of Mars are attainable. With a minimal amount of additional research into the effects of sun light absorption into Martian soil we could very well be able to terraform a small area of Mars.

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