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# Orbiting Laser Beacons for Adaptive Optics Observations of Mars and Other Planets

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**ABSTRACT.** The use of adaptive optics to correct the effects of seeing is rapidly becoming a standard technique in astronomical observing and is fundamental to current plans for extremely large telescopes. Adaptive optics has proved effective for studies of small solar system objects that can be used as their own reference sources. However, it is much harder to apply adaptive optics techniques to bright planets such as Mars and Venus, because of the difficulty of finding a suitable reference star that is not drowned out by the intense scattered light from the planet itself. A possible solution to the problem might be provided by current plans for laser communications systems. For example, the *Mars Telecommunications Orbiter*, planned for launch in 2009, will carry a 5 W laser to beam data back to Earth. This laser system in orbit around Mars will provide a very bright guide star, with a magnitude ranging from 1.8 to 5.8. Such a guide star is more than bright enough for existing adaptive optics systems and is in the range needed to support “extreme AO” systems, producing very high Strehl ratios. Used in conjunction with large ground-based telescopes, this could allow studies of Mars with spatial resolutions down to a few kilometers and allow the ground-based study of Mars to extend around much of its orbit, rather than be limited to the time around opposition.

## 1. INTRODUCTION

Ground-based observations of solar system objects have, until recently, been limited to relatively coarse spatial resolutions by the effects of seeing in the Earth’s atmosphere. However, the situation is changing with the development of adaptive optics (AO) systems on large telescopes. In principle, such systems should make possible diffraction-limited spatial resolution in the near-infrared region of the spectrum. Such systems are now coming into use as common-user facilities on most 1–8 m class telescopes (e.g., Keck, ESO VLT, Gemini, and Subaru).

These systems have indeed proved effective in observations of the smaller objects in the solar system—objects that are small enough to be used as their own reference sources. For example, AO observations have been used to study the surface and clouds of Titan (Roe et al. 2002; Coustenis et al. 2001), the volcanic activity on Io (Marchis et al. 2000), the Pluto-Charon system (Close et al. 2000), and to detect satellites of minor planets (Merline et al. 2003).

However, AO techniques are much harder to apply to planets such as Mars and Venus, our nearest neighbors in the solar system. These planets are nevertheless extremely interesting targets for high-resolution ground-based observations, and their study forms part of the science case proposed for future extremely large (≥30 m) telescopes (Gilmozzi et al. 2002; Hawarden et al. 2003).

## 2. THE IMPORTANCE OF AO OBSERVATIONS OF MARS AND VENUS

Mars and Venus are the Earth’s nearest neighbors and closest analogs in the solar system, and their study can tell us much about the evolution of terrestrial planets, at a time when we are beginning the search for such planets around other stars. Observations in the near-IR, the wavelength region in which the gains of AO are most significant, can reveal many details about the surface and atmosphere of these planets.

This wavelength region includes absorption bands of $CO_2$, the main atmospheric component of Mars, as well as a number of trace gases. The $CO_2$ band strength can be used as a measure of the surface atmospheric pressure (Bibring et al. 1991; Bailey et al. 2004) and can thus be used to observe pressure changes due to weather systems (Barnes 1981; Collins et al. 1996). Such observations could provide one of the key inputs needed to constrain general circulation models of the Martian atmosphere (e.g., Forget et al. 1999). They can also provide information on the dust content of the atmosphere (by comparing different $CO_2$ bands). There are also strong near-IR absorption bands due to both $H_2O$ and $CO_2$ ice that can be used to study both the surface ice associated with the polar caps (Calvin & Martin 1994) and $H_2O$ and $CO_2$ ice clouds (Bell et al. 1996). The 2–2.5 $\mu$m region also includes absorption features due to hydrated clay minerals, sulphates, and carbonates, which would provide further evidence for the presence of water in the past.

In the case of Venus, near-IR observations of the night side of the planet reveal thermal radiation from the surface and

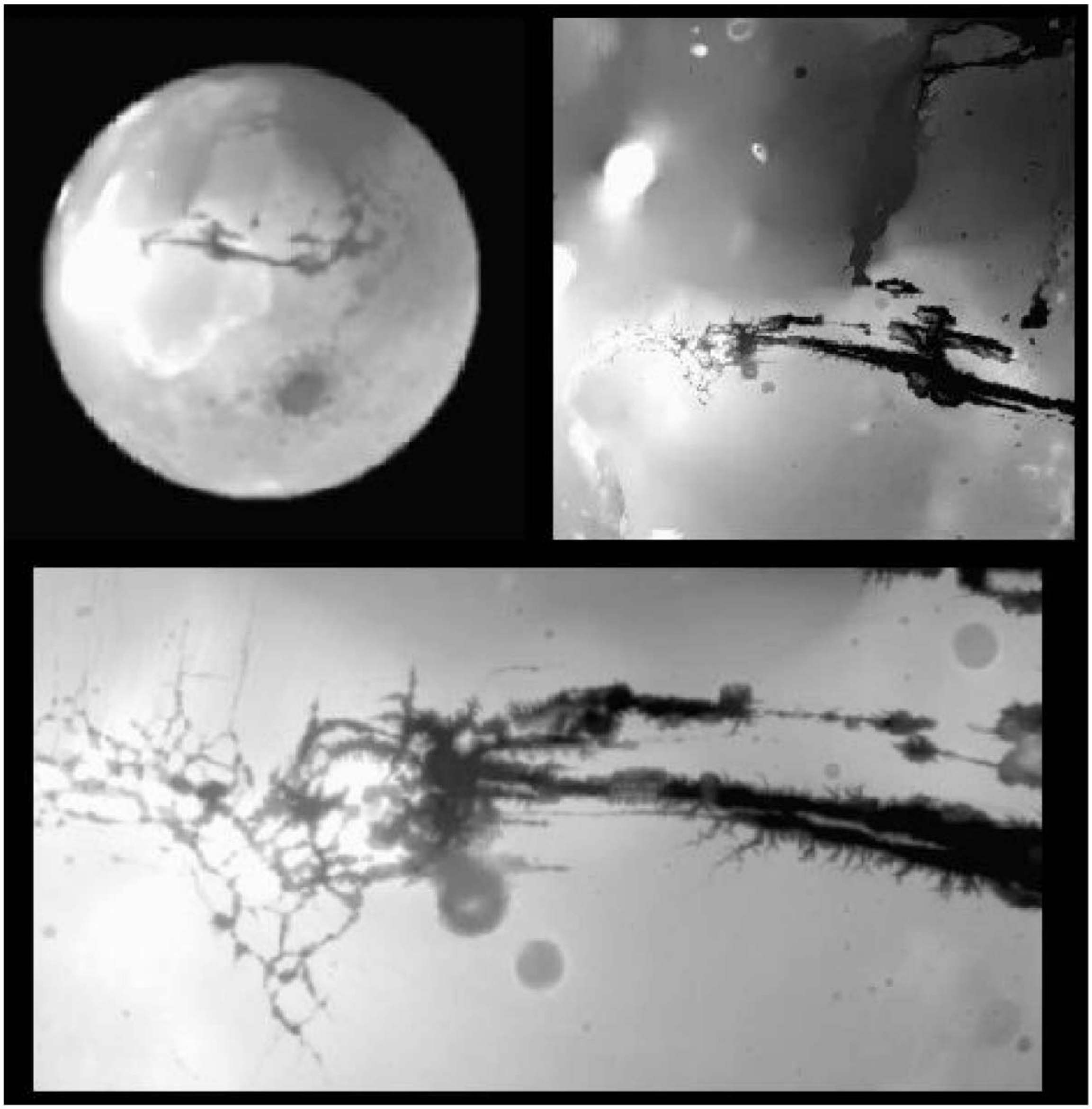

FIG. 1.—Resolution on Mars achievable with adaptive optics. *Mars Global Surveyor* MOLA topography data has been plotted at three different resolutions: 90 km (*top left*), close to what is achievable with seeing-limited observations in excellent seeing when Mars is at its closest approach; 16 km (*top right*), corresponding to the diffraction limit of an 8 m telescope at 2 $\mu$m under the same conditions; 4 km (*bottom*), the diffraction limit of a 30 m telescope under the same conditions.

lower atmosphere through a number of "windows" between strong $CO_2$ and $H_2O$ absorption bands (Allen & Crawford 1984; Crisp et al. 1991). Observations in these windows can be used to study the structure of the lower atmosphere (Meadows & Crisp 1996) and the structure and properties of the sulphuric acid clouds. High spatial resolution observations of the cloud patterns (which show high contrast in the 2.2–2.4 $\mu$m region) can be used to study the dynamics of this region, which shows rotation periods in the range of 5–8 days.

Finally, airglow emission in the $O_2$ $^1\Delta_g$ feature at 1.27 $\mu$m is seen in both Venus (Connes et al. 1979) and Mars (Noxon et al. 1976). The Venus airglow is strong and highly variable (Crisp et al. 1996) and provides a probe of the dynamics of the upper atmosphere. High spatial resolution observations would enable more detailed study of the airglow variability on short timescales.

Figure 1 shows the resolution that might be obtained with adaptive optics in the case of Mars. Diffraction-limited observations with an 8 m telescope would give a resolution of about 16 km at 2 $\mu$m wavelength during a perihelic opposition, and

TABLE 1
POWER RECEIVED AT EARTH FROM THE *MTO* LASER SYSTEM

| Phase | Distance (AU) | Power (W m$^{-2}$) | Photon Rate (photons s$^{-1}$ m$^{-2}$) | AB Magnitude | Footprint Size (km) |
|---|---|---|---|---|---|
| Conjunction ............. | 2.4 | $4.83 \times 10^{-12}$ | $2.56 \times 10^{7}$ | 5.8 | 3100 |
| Typical .................. | 1.0 | $2.79 \times 10^{-11}$ | $1.48 \times 10^{8}$ | 3.9 | 1290 |
| Aphelic opposition ....... | 0.66 | $6.40 \times 10^{-11}$ | $3.39 \times 10^{8}$ | 3.0 | 850 |
| Perihelic opposition ...... | 0.37 | $2.02 \times 10^{-10}$ | $1.07 \times 10^{9}$ | 1.8 | 480 |

this improves to 4 km with a 3 m telescope. Perhaps more importantly, AO observations with an 8 m or larger telescope allow resolutions of 100 km or better throughout the entire orbit of Mars, making long-term studies of seasonal variation possible. Similar resolutions can be achieved for Venus.

Of course, studies of this type will also be made from orbiting spacecraft. However, ground-based observing offers a number of significant advantages. Instruments on ground-based telescopes are not subject to the constraints on size, mass, power, and data rates that apply to space instruments. Thus, large high spectral resolution imaging spectrographs that could not currently be considered for a Mars orbiter can be used. For example, CRIRES on the ESO Very Large Telescope (Moorwood et al. 2003) will allow spatially resolved near-IR spectroscopy with a resolving power up to 100,000. This resolution could be extremely valuable for the study of the trace gas content of planetary atmospheres. The highest resolving power currently available for this in a space-based instrument is around 5000, for the Planetary Fourier Spectrometer on *Mars Express*.

Ground-based observing also allows near-simultaneous views of an entire hemisphere of Mars and provides local time coverage and high time resolution that is not possible from a low-resolution mapping orbit such as that used by the *Mars Global Surveyor*. All of these features are particularly valuable for studies of the Martian atmosphere and climate.

## 3. PROBLEMS WITH AO OBSERVATIONS OF MARS AND VENUS

The problem with AO observations of Mars and Venus is that of finding a suitable reference source for the wave-front sensor. Adaptive optics systems require a bright reference source as close as possible to the target being observed. However, in the case of bright planets, because of the effects of scattered light, the very bright sky around the planet will also be seen by the wave-front sensor, and this will seriously degrade its performance, requiring an even brighter star than usual. The probability of there being a suitably bright natural guide star close to the planet is very small. In the case of Mars, we could consider using its brightest satellite, Phobos, which reaches a magnitude of 10.4 when Mars is at its closest approach. In a dark sky, this would be bright enough to use as a reference source, but in the bright sky around Mars, even this has been found to be inadequate.

Even if a suitable reference star could be found, the size of these bright planets is such that the star is likely to be some distance from the center of the planet, and even further from its far edge. The performance of an AO system seriously degrades if the reference source is far off-axis. For example, figures from NAOS/CONICA on the ESO Very Large Telescope (Brandner et al. 2003) show that with a 10th magnitude reference star in 0″.8 seeing, the Strehl ratio is 0.49 for an on-axis reference source, but falls to 0.09 for a reference source 30″ off-axis.

The situation with Venus is even worse than that of Mars. Since Venus always remains close to the Sun, it is seldom possible to observe it in a dark sky, and most observations have to be made in twilight or daylight. Venus is bright enough that near-IR observations are perfectly possible in daylight, but most wave-front sensors operate in the visible and would not be able to cope with daylight operation.

Artificial laser guide stars, which are made by exciting the sodium layer in the Earth's atmosphere with a laser on the ground, help the situation, but do not solve the problem completely. A natural guide star is still needed with a laser guide star system to provide the tip-tilt part of the correction, which cannot be obtained from the laser guide star.

## 4. ORBITING LASER BEACONS

An effective solution for enabling AO observations of bright planets such as Mars would be to place a laser beacon in orbit around the planet itself. This may seem an expensive solution to the problem; however, such systems may well become available as a result of plans for optical communications systems. Optical wavelengths used for communications from spacecraft have the potential to offer much higher rates of data transmission than are possible at radio wavelengths, because the shorter wavelengths can be much more tightly beamed to the receiver (Bland Hawthorn et al. 2002).

The *Mars Telecommunications Orbiter* (*MTO*; Jet Propulsion Laboratory 2003), which is being designed for launch in 2009, includes an experimental optical communications payload that uses a 5 W (average) power laser operating at a 1.064 $\mu$m wavelength through a 30 cm aperture telescope. It will be used in conjunction with a ground-based receiving station on Earth and is expected to obtain data rates of 10–100 Mbps. However, such a device could also be used as a guide star for AO observations of Mars.

Table 1 lists the power that would be received from such a laser system at Earth for various Mars distances. It is assumed that the transmitting telescope is diffraction limited and that the overall throughput of the optics and the Earth atmosphere is 50%. The footprint size of the beam at the Earth (measured at the first zero of the diffraction pattern) is also listed. The flux has also been quoted for the AB magnitude (Oke & Gunn 1983), which would be measured in a broadband filter of a 10% width (since the source is monochromatic, its magnitude depends on the width of the assumed band) and as a photon rate.

The magnitudes and photon rates are very bright. They are more than adequate to support current AO systems designed for natural guide stars, and are in the range needed to support proposed "extreme AO" systems offering very high Strehl ratios (Angel 1994; Macintosh et al. 2002). Such high-order AO systems might also enable reseachers to achieve good levels of correction at both visible and near-IR wavelengths. In addition to its brightness as a guide star, another important advantage of an orbiting laser beacon is its monochromatic spectrum. This would allow the use of narrowband filters to improve the contrast of the guide star relative to the background light of Mars. The radiance of Mars is about $8.4 \times 10^{-10}$ W $\mathrm{m}^{-2}$ $\mu\mathrm{m}^{-1}$ $\mathrm{arcsec}^{-2}$ at 1.064 $\mu$m (calculated from the solar flux at a distance of 1.524 AU from the Sun reflected by a surface with an albedo of 0.4, which is appropriate to the bright regions of Mars at this wavelength; Bell et al. 1999). A filter with a bandwidth of less than 30 nm will reduce the background light from Mars within 1 $\mathrm{arcsec}^2$ to less than that of the guide star for Mars-Earth distances up to 1 AU, and a filter of less than 5 nm would do the same for Mars at any distance. This means that it is quite feasible to use such a guide star when it is in front of Mars, thus minimizing the off-axis distance and maximizing the AO correction.

Since the radiance of the daylight sky on Earth is similar to that of Mars ($2.35 \times 10^{-10}$ W $\mathrm{m}^{-2}$ $\mu\mathrm{m}^{-1}$ $\mathrm{arcsec}^{-2}$ at 1.064 $\mu$m; Ortiz et al. 2000), the operation of such a system in daylight should also be quite feasible. This is important, since daylight observations are necessary if Mars is to be followed throughout its orbit. It also means that an extensive Mars monitoring program might be conducted on a large ground-based telescope without significantly impacting nighttime observing. Were a system like the *MTO* ever to be placed in orbit around Venus, AO observations of that planet, which has to be observed in twilight or daylight, should also be feasible, although narrower filters may be required to allow for the brightness of the planet.

The use of an orbiting laser beacon should require little modification to existing AO systems. The wave-front sensor needs to be able to operate at the laser wavelength of 1.064 $\mu$m. This is near the upper end of the wavelength range of silicon CCD detectors, so quantum efficiency may be low. However, in view of the brightness of the source, it may still be adequate. A wave-front sensor based on an IR detector such as a HgCdTe or InGaAs array should provide better performance. The wave-front sensor needs to be equipped with a filter to isolate the laser wavelength as described above. Because of the narrow footprint at Earth, the spacecraft laser transmitter must accurately point at the observatory. If AO observing is to be done in parallel with communications experiments, then the AO telescope would need to be on the same site (or at least within a few hundred kilometers) of the receiving station. Alternatively, the transmitter would have to be specifically pointed at an observatory to allow AO observations. In either case, the most effective use of the *MTO* or similar spacecraft for AO observations is only likely to be achieved if such considerations are factored into mission plans at an early stage.

## 5. CONCLUSIONS

Laser data transmitters such as the optical communications payload planned for the *Mars Telecommunications Orbiter* could be used as reference sources to facilitate adaptive optics observations—in this case, of Mars—with large ground-based telescopes. The laser beacon would be bright enough to allow high-Strehl AO correction at near-IR wavelengths, as well as useful correction at visible wavelengths. This would enable resolutions down to a few kilometers at opposition, and would also make possible observations with useful resolutions throughout the orbit of the planet. Daylight observation would also be feasible. A system of this type would be particularly valuable for studies of the Mars atmosphere and climate using IR spectroscopy. A similar system in orbit around Venus would be equally valuable for studies of that planet.

## REFERENCES

Allen, D.A., & Crawford, J. W. 1984, Nature, 307, 222

Angel, J. R. P. 1994, Nature, 368, 203

Bailey, J., Chamberlain, S., Walter, M., & Crisp, D. 2004, in Mars: The Search for Life, ed. R. A. Harris (Noordwijk: ESA), in press

Barnes, J. R. 1981, J. Atmos. Sci., 38, 225

Bell, J. F., Calvin, W. M., Ockert-Bell, M. E., Crisp, D., Pollack, J. B., & Spencer, J. 1996, J. Geophys. Res., 101, E4, 9227

Bell, J. F., et al. 1999, Icarus, 138, 25

Bibring, J.-P., et al. 1991, Planet. Space Sci., 39, 225

Bland Hawthorn, J., Harwit, A., & Harwit, M. 2002, Science, 297, 523

Brandner, W., Lidman, C., & Moutou, C. 2003, NAOS-CONICA User Manual (Garching: ESO), 1.5.1

Calvin, W. M., & Martin, T. Z. 1994, J. Geophys. Res., 99, 21, 143

Close, L. M., Merline, W. J., Tholen, D. J., Owen, T. C., Roddier, F. J., & Dumas, C. 2000, Proc. SPIE, 4007, 787

Collins, M., Lewis, S., Read, P., & Hourdin, F. 1996, Icarus, 120, 344

Connes, P., Noxon, J. F., Traub, W. A., & Carleton, N. P. 1979, ApJ, 233, L29

Coustenis, A., et al. 2001, Icarus, 154, 501

Crisp, D., Allen, D. A., Grinspoon, D. H., & Pollack, J. B. 1991, Science, 253, 1263

Crisp, D., Meadows, V., Bezard, B., DeBergh, C., Maillard, J.-P., & Mills, F. 1996, J. Geophys. Res., 101, 4577

Forget, F., et al. 1999, J. Geophys. Res., 104, 24, 155

Gilmozzi, R., Dierickz, P., & Monnet, G. 2002, in Beyond Conventional Adaptive Optics, ed. E. Vernet (Garching: ESO), 1

Hawarden, T., et al. 2003, Proc. SPIE, 4840, 299

Jet Propulsion Laboratory 2003, Mars Telecom Orbiter: Spacecraft Design Study: Mission and Payload Description, Requirements, and Constraints (Pasadena: JPL), http://acquisition.jpl.nasa.gov/rfp/mtodesignstudies/exhibit1.pdf

Macintosh, B. A., et al. 2002, Proc. SPIE, 4494, 60

Marchis, F., et al. 2000, Icarus, 160, 124

Meadows, V. S., & Crisp, D. 1996, J. Geophys. Res., 101, 4595

Merline, W. J., Close, L. M., Dumas, C., Chapman, C. R., Menard, F., Tamblyn, P. M., & Durda, D. D. 2003, BAAS, 35, 972

Moorwood, A. F. M., et al. 2003, Proc. SPIE, 4841, 1592

Noxon, J. F., Traub, W. A., Carleton, N. P., & Connes, P. 1976, ApJ, 207, 1025

Oke, J. B., & Gunn, J. E. 1983, ApJ, 266, 713

Ortiz, G. G., Sandusky, J. V., & Biswas, A. 2000, JPL TMO Progress Report (Pasadena: JPL), 42

Roe, H. G., de Pater, I., Macintosh, B. A., & McKay, P. 2002, ApJ, 581, 1399