LIDAR Technology for measuring trace gases on Mars and Earth

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ABSTRACT

Many fundamental questions about planetary evolution require monitoring of the atmosphere with unprecedented accuracy at both high and low latitudes, over both day and night and all seasons. Each planetary atmosphere presents its own unique challenges. For the planets/moons that have relatively low surface pressure and low trace gas concentrations, such as Mars or Europa, the challenge is to have enough sensitivity to measure the trace gas of interest.

Trace gases and isotopic ratios in planetary atmospheres offer important but subtle clues as to the origins of the planet's atmosphere, hydrology, geology, and potential for biology. An orbiting laser remote sensing instrument is capable of measuring trace gases on a global scale with unprecedented accuracy, and higher spatial resolution that can be obtained by passive instruments. For Mars our proposed measurement technique uses Differential Absorption Lidar (DIAL) in the 3-4 um spectral range to map various trace gas concentrations from orbit on a global scale. For earth, we can use the same technique at 1.65 um to measure methane concentrations, a strong greenhouse gas. The instrument uses Optical Parametric Amplifiers (OPA) for the transmitter along with photon counting detectors to achieve the necessary sensitivity.

1. INTRODUCTION

The recent discovery of methane on Mars [1] has intensified interest in a trace gas detection orbital instrument to identify sources of methane and pinpoint their locations. Laser remote sensing measurements of trace gases from orbit can provide unprecedented information about important planetary science and answer critical questions about planetary atmospheres. Remotely measuring methane (CH4) and other biogenic molecules (such as ethane and formaldehyde) on Mars has important implications on the existence of life on the red planet. Measuring CH4 at very low (<1 ppb) concentrations from orbit will dramatically improve the sensitivity and spatial resolution in the search for CH4 vents and sub-surface life.

However, methane is very important on earth also. Currently, observations of greenhouse gases are limited to in-situ (surface and tower) and sparse airborne in-situ measurements. Accurate, global observations are needed in order to better understand climate change and reduce the uncertainty in the carbon budget. Although CO2 is currently the primary greenhouse gas of interest, methane can have a much larger impact on climate change. Methane levels have remained relatively constant over the last decade but recent observations in the Arctic have indicated that levels may be on the rise due to permafrost thawing. NASA's Decadal Survey [2], underscored the importance of methane as a greenhouse gas by stating : "Lidar CO2 and O2 measurements should be complemented by a CO sensor, either as part of the CO2 satellite or by coordination with a "chemical-weather" mission…Ideally, to close the carbon budget, methane should also be addressed, but the required technology is not now obvious. If appropriate and cost-effective methane technology becomes available, methane capability should be added".

Methane has absorptions in the mid-infrared (3.3 um). This spectral region is ideal for planetary (Mars) methane monitoring, but unfortunately is not suitable for earth monitoring since the CH4 lines are severely interfered with by water (H2O). The near infrared overtones of CH4 at 1.65 um are relatively free of interference from other atmospheric species.

2. METHANE ON MARS

Major trace gas targets for planetary science include Mars, Europa, Titan, comets and asteroids and interstellar molecular clouds. Each planetary atmosphere presents its own unique challenges. For the planets/moons and other celestial bodies that have relatively low surface pressure and low trace gas concentrations, such as Mars or Europa, the challenge is to have enough sensitivity to measure the trace gas of interest. For other bodies, such as Titan, which have relatively high surface pressure the challenge, is to detect the trace gas of interest without interference from other species.

In the case of Mars, a very high priority target in any future astrobiology and exploration mission, the challenge would be to build an instrument with high enough sensitivity to measure methane and other biogenic markers and be able to distinguish between organic and inorganic sources of these markers. In order measure trace gases remotely two major technology components are needed:

1) A transmitter with a tunable laser source with sufficient energy, whose spectral emission will overlap the gas absorption lines.

2) A receiver with a sensitive detector to detect the reflected laser energy

Most trace gas molecules of interest have very strong spectral absorption features in the 3 - 4 µm region, thus using transmitter in this region will enhance the sensitivity od the measurement. Our instrument will

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generate and detect tunable laser signals in the 3 - 4 µm region to take advantage of these strong molecular absorptions and allow detection of small gas concentrations

The instrument will operate in a nadir viewing geometry, and measure the strong laser echoes from the planetary surface. The instrument's tunable, narrow-frequency light source and sensitive photon-accumulation detection will allow a much higher spatial resolution and higher sensitivity than passive spectrometers, such as FTIRs. Additionally our lidar can make continuous measurements from orbit, in all seasons, in sunlight and darkness and at all latitudes (including over Polar Regions).

A laser transmitter will generate tunable laser radiation in the 3 - 4 µm band. The laser frequency can be accurately and rapidly tuned between off-line and the peaks of the strong trace gas absorption lines, permitting determination of their full absorption signatures. A mid-infrared detector, adapted will enable very high detection sensitivity. Using these together in a sounding (surface reflection) mode enables DIAL measurements from orbit with modest laser power. All these technologies together allow much higher spatial resolutions and sensitivities than with passive spectrometers.

The measurement sensitivity depends on integration time, which can be selectable via ground processing. The orbital platform and small laser footprint allows for the identification of areas with higher gas concentrations as prime targets for more detailed future investigations using a lander equipped with in-situ instrumentation.

The Mars atmosphere is well suited for trace gas measurements using lasers. The average surface pressure is ~7 mbar, which minimizes pressure broadening and results in narrow linewidth absorption lines. For example, the Doppler width of a CH4 line at 3057.726 cm-1 (3270.404 nm) is 0.0079 cm-1 (237 MHz). With such narrow spectroscopic features a high resolution spectrometer is needed to increase the detection sensitivity. A laser spectrometer can have 0.000033 cm-1 (1 MHz) resolution.

3. METHANE ON EARTH

The recent report of the Intergovernmental Panel on Climate Change [3] attributes the dramatic increase of the atmospheric concentrations of greenhouse gases from their pre-industrial age levels mostly to anthropogenic sources and the burning of fossil fuels. As the concentration of greenhouse gases steadily increases the subsequent radiative forcing could have a significant impact on the earth's climate. Although the exact nature and magnitude of any future climate change is difficult to accurately model and predict, its potential consequences can be dramatic and have major global implications. It is therefore extremely important to understand the mechanisms and driving forces behind climate change (e.g. the increase in greenhouse gases) and assess the potential impact on the globe. Despite the enormous implications of climate change our present knowledge of greenhouse gas concentrations and the carbon cycle budget is incomplete.

Currently our observations of greenhouse gases are limited to in-situ (surface and tower sites) and sparse airborne measurements. CO2 is currently the primary greenhouse gas of concern but other trace gases such as methane could have a much larger impact on climate change. Although methane survives for a shorter time in the atmosphere than CO2 its impact on climate change can be more than 20 times than that of CO2. Methane levels have remained relatively constant over the last decade around 1.78 parts per million (ppm) (Figure 1) but recent observations indicate that levels may be on the rise.

A current hypothesis holds that vast reservoirs of methane are trapped in the permafrost regions of northern Canada, Europe, and Siberia and as global temperatures rise and the permafrost thaws, enormous amounts of methane will be released into the atmosphere affecting the vegetation and ecosystems. Another hypothesis points to increased production of methane by microbes as the permafrost warms up and temperatures rise. Although the exact mechanism may still be uncertain its implications are not: Increasing methane concentrations can trigger a positive feedback effect where increasing temperatures result in increasing methane levels creating a "runaway" greenhouse effect.

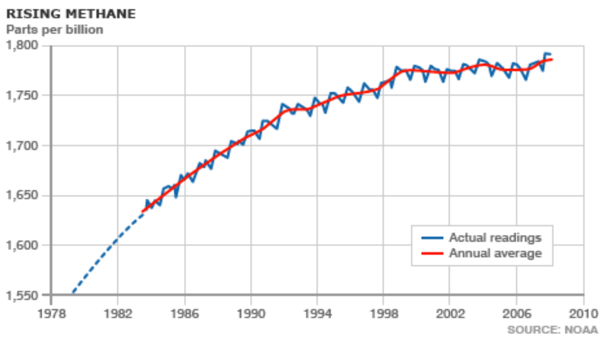

Figure 1. *Methane Levels since 1978 (source: NOAA).*

Methane has absorptions in the mid-infrared (3.3 um). This spectral region is ideal for planetary (Mars) methane monitoring, but unfortunately is not suitable for earth monitoring since the CH4 lines are severely interfered with by water (H2O). The near infrared overtones of CH4 at 1.65 um are relatively free of interference from other atmospheric species.

4. TECHNOLOGY

The 3 - 4 um spectral region is accessible with Optical Parametric Generation (OPG) techniques. In OPG, a photon of an incident laser pulse (pump) is divided into two photons by a nonlinear optical crystal. When the pump power is high enough any photons that satisfy the energy and phase matching conditions are amplified.

Optical Parametric Amplifiers (OPA) are a seeded version of OPG. Laser light from a signal beam propagates through a non linear crystal together with a pump beam of shorter wavelength and only the seed signal is amplified and an idler is generated. The idler energy (wavelength) is the difference between the seed and the pump.

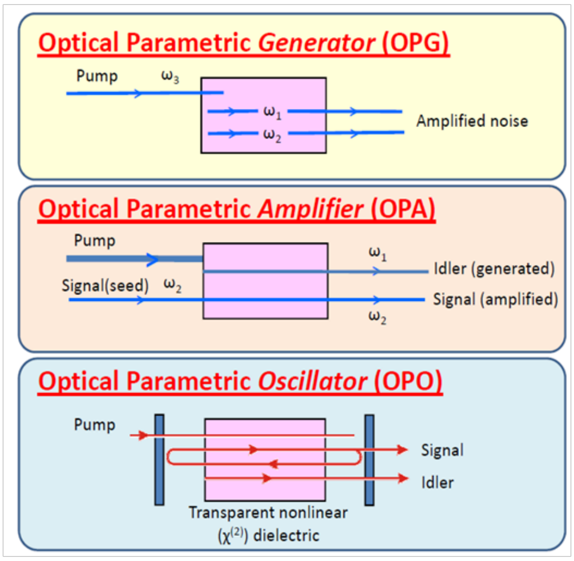

Figure 2.*OPG, OPA, OPO Functional Block Diagrams.*

Finally an Optical Parametric Oscillator (OPO) can be regarded as an OPA with optical feedback. The non-linear crystal is placed inside a cavity just like a laser crystal in laser resonator cavity. The differences between these methods are illustrated in Figure 2.

5. RESULTS

At Goddard Space Flight Center (GSFC) we have developed an OPA system that we believe may be suitable for both Mars and Earth applications.

A functional block diagram of the OPA system is shown in Figure 3.

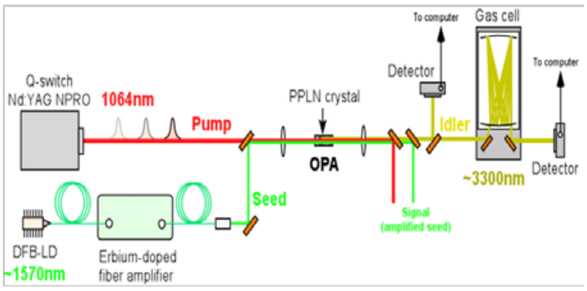

Figure 3.*OPG, OPA, OPO Functional Block Diagram.*

A single frequency Nd:YAG laser (pump) is combined with an amplified seed diode laser and directed through a non-linear crystal which generates the IR radiation. The infrared beam is then directed through a cell and onto an IR detector. The seed wavelength is scanned over the methane absorption and a computer digitizes the photo detector signal.

Although methane has many absorptions in the 3-4 um region we initially targeted a set of three lines at 3270.40 nm. These lines have very strong line strengths and are not interfered with by CO2, the major atmospheric constituent on Mars. They are closely spaced together and provide a unique spectroscopic signature for methane. Since the surface pressure on Mars is very low (typically 6-7 mbar) any pressure broadening of the line would be negligible.

Figure 4 shows a scan of the 3270.40 nm methane lines in a cell. The pressure was 2.06 Torr and the methane concentration was 2.9%

The agreement between the expected absorption as calculated from the 2004 HITRAN database and the OPA systems is excellent.

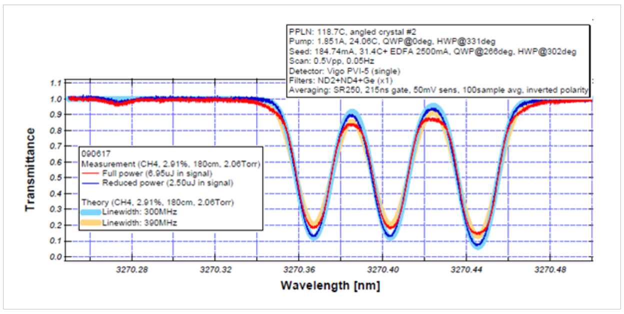

Figure 4.*Scan of methane lines at 3270.40 nm using the GSFC OPA system.*

The same system has been used to generate 1.65 um radiation for the earth application.

Figure 5 shows a scan of the 1650.96 nm methane lines in a cell. The pressure was 200 Torr and the methane concentration was 100%.

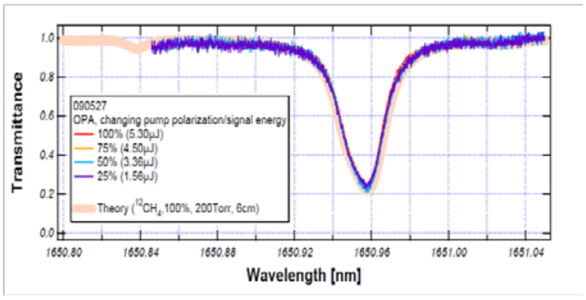

Figure 5.*Scan of methane lines at 1650.96 nm using the GSFC OPA system.*

A side benefit of the OPA system is that both 3.3 and 1.58 um radiation may be produced simultaneously.

Figure 6 shows a scan of the 3270.40 nm methane lines and simultaneous detection of CO2. This is important for a Mars application where atmospheric CO2 monitoring may provide additional information along with methane detection.

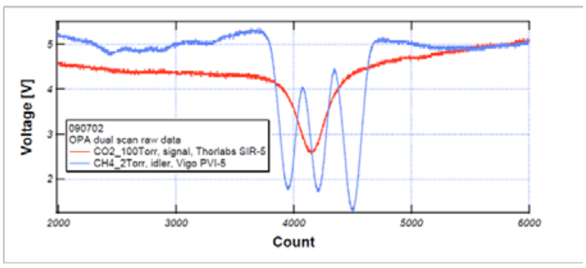

Figure 6.*Simultaneous scan of CH4 and CO2 using the GSFC OPA system.*

6. SUMMARY

Trace gases and isotopic ratios in planetary atmospheres offer important but subtle clues as to the origins of the planet's atmosphere, hydrology, geology, and potential for biology. An orbiting laser remote sensing instrument is capable of measuring trace gases on a global scale with unprecedented accuracy, and higher spatial resolution that can be obtained by passive instruments. For Mars our proposed measurement technique uses Differential Absorption Lidar (DIAL) in the 3-4 um spectral range to map various trace gas concentrations from orbit on a global scale. For Earth, we can use the same technique at 1.65 um to measure methane concentrations, a strong greenhouse gas. The instrument uses Optical Parametric Amplifiers (OPA) to achieve the necessary detection sensitivity. Preliminary results demonstrating CH4 detection using the present OPA configuration show considerable promise.

REFERENCES

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