Miniaturized Hollow-Waveguide Gas Correlation Radiometer (GCR) For Trace Gas Detection in the Martian Atmosphere

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Search for life

Methane

Serpentization Reactions
(ancient olivine-bearing crustal rocks)

Preserved through formation of clathrate
hydrates & released through climate change

Geologic sources
(gas seeps, volcanoes)

Life?
(methanogens)

How much is there?

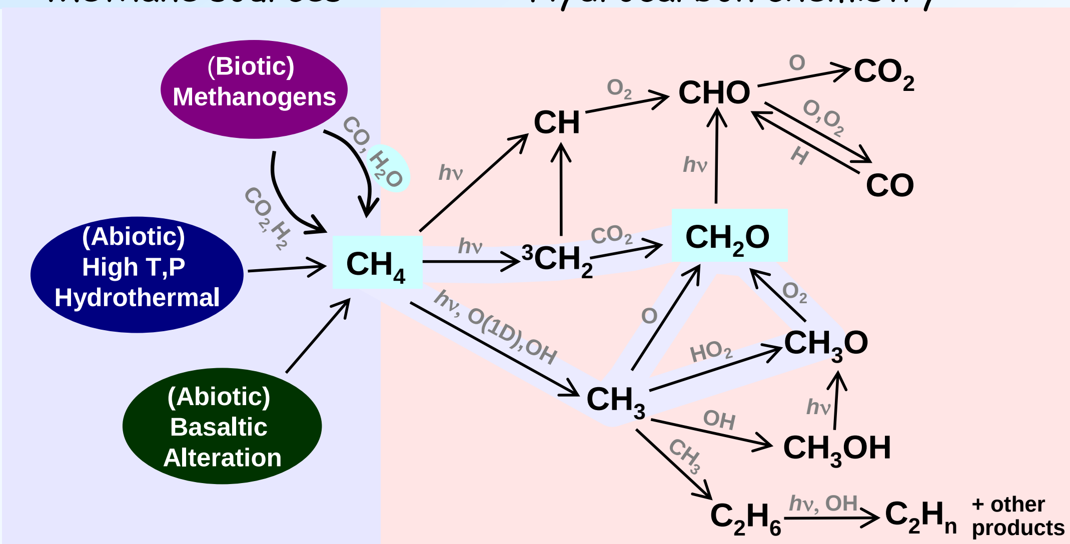
10 ppbv (± 5 ppbv): Formisano, *et al.*, using the Planetary Fourier Spectrometer (PFS) onboard the Mars Express Orbiter

200 ppbv in equatorial regions, 20 to 60 ppbv at poles: Mumma, *et al.* using spectrometers at NASA Infrared Telescope Facility in Hawaii and the Gemini South telescope in Chile

Calculated global average of 11 ppbv, range of 7 to 15 ppbv: Krasnopolsky, *et al.* using a spectrometer on the Canada-France-Hawaii Telescope in Hawaii

Atmospheric Chemistry

Possible
Methane sources / Hydrocarbon chemistry



(Adapted from Atreya, et al.)

(adapted from Wong, *et al.*)

On Earth, subterranean and oceanic microbes produce methane through metabolism

$4CO + 2H_2O \rightarrow CH_4 + 3CO_2$

$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$

On Mars, methane has a relatively short photochemical lifetime (300 Earth years).

Destruction lifetimes are even shorter (a few months to several years)

formaldehyde lifetime is only 7.5 hours - *presence of formaldehyde, indicates a continuous source of methane…*

This lifetime is several orders of magnitude longer than typical atmospheric transport timescales

First order approximation: methane should be well mixed in the atmosphere *except over regions of the surface where it is being produced or actively depleted*

Shorter destruction lifetimes indicate another removal process *This could explain the observed uneven distribution*

CH_4 that we see in the atmosphere now was probably not produced billions of years ago

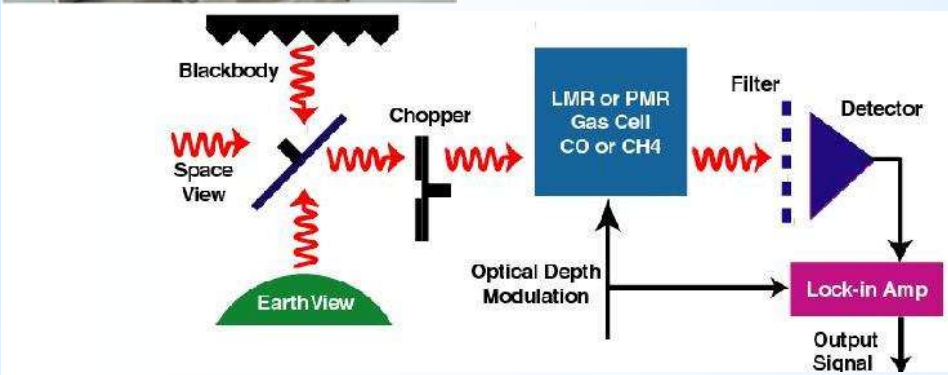
Miniaturized Gas Correlation Radiometer
Heritage

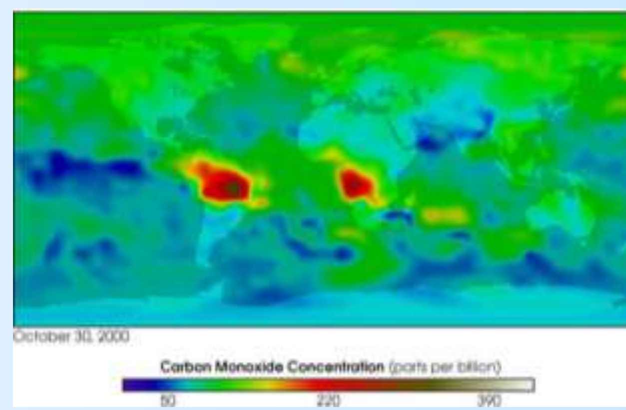
MOPITT (Measurements of Pollution in the Troposphere)

http://mopitt.eos.ucar.edu/Instrument/

- Nadir viewing gas correlation radiometer
- Measures column CO and CH_4 in 2.3 mm region
- Measures profiles of CO in 4.6 mm region
- Horizontal resolution (CO and CH_4): 22 x 22 km
- Vertical resolution (for CO): 3 km
- Precision requirements:
  - Column CO: 10% (~10 ppbv)
  - Column CH_4: 1% (~ 16 ppbv)
  - Profiles CO: 10%

Terra Satellite EOS AM-1 (**E**arth **O**bserving **S**ystem) in sun-synchronous orbit. Launched on Atlas IIAS vehicle in December 1999, started collecting data in February 2000.

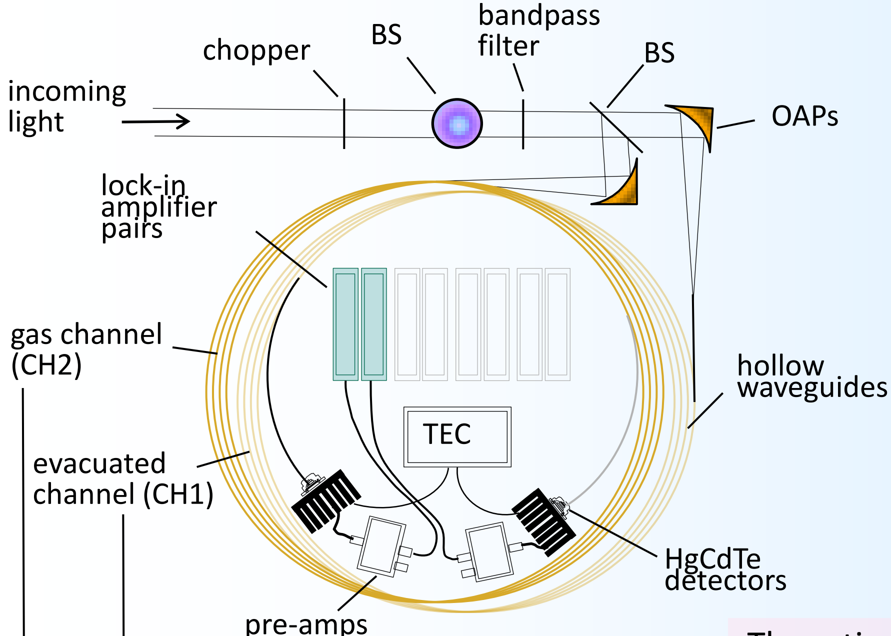




How does MOPITT get high precision from a short gas cell?
- Length Modulation Radiometer (LMR) changes gas path length thus modulating the gas amount
- Pressure Modulation Radiometer (PMR) changes the cell gas pressure with a piston

Miniaturized Gas Correlation Radiometer
Technical Approach

Correlation: Gas cell spectral lines align perfectly with the incoming radiance spectral lines

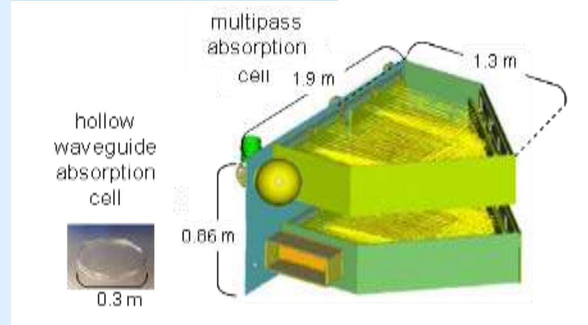


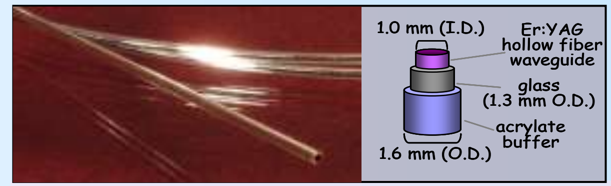
Evacuated fiber sensitive to changes in atmospheric absorption by the trace gas

Gas filled fiber used as a spectral filter blocks absorption - sensitive to changes in solar flux

The ratio of these channels is sensitive to changes in absorption but not to changes in solar flux

Miniaturization





Replacement of a multipass cell with a hollow waveguide reduces mass and volume by >99% - making gas correlation radiometry viable for Mars missions[1]

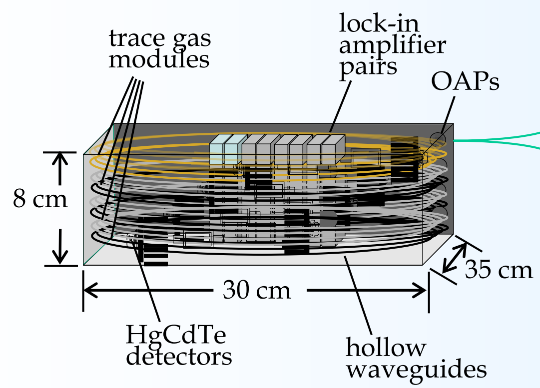
Selectivity

- Narrow bandpass filter selects wavelength region with targeted lines
- Unwanted trace gases are removed by filling both cells with interfering gas

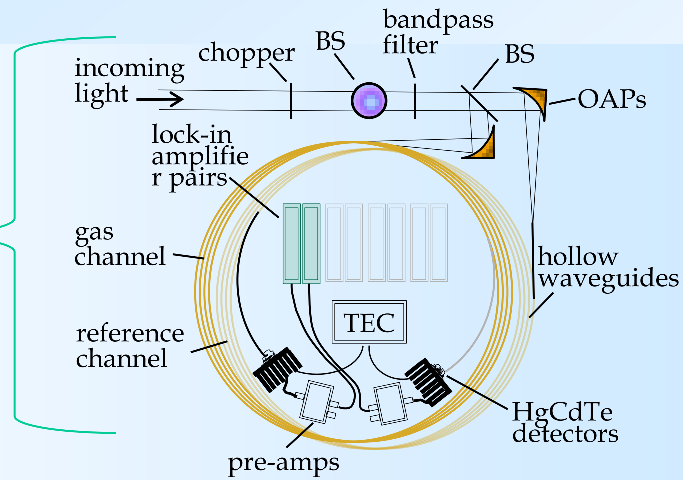
[1]Tolton, B. T., Hackett, J., Caldwell, D. & Miller, D. Strawman design for a gas-filter correlation radiometer satellite instrument to measure the atmospheric CO_2 column. *Proc. of SPIE* **5543**, 332-337 (2004).

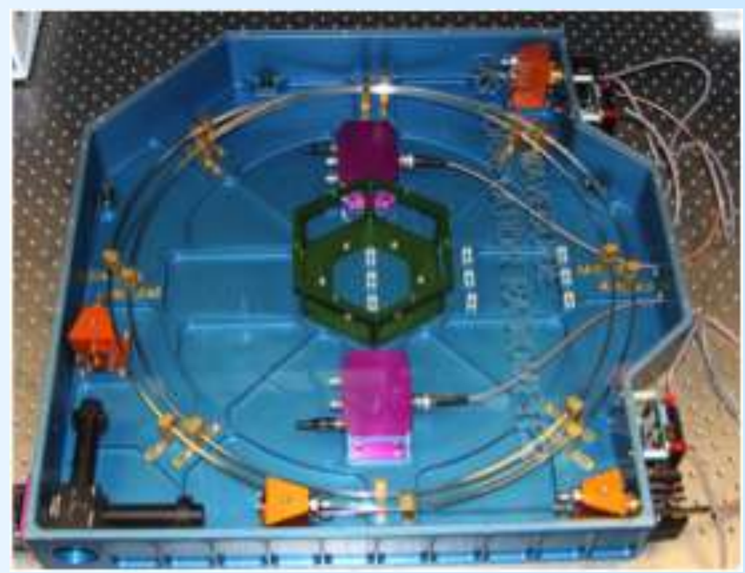
Modular design

Multi-gas instrument

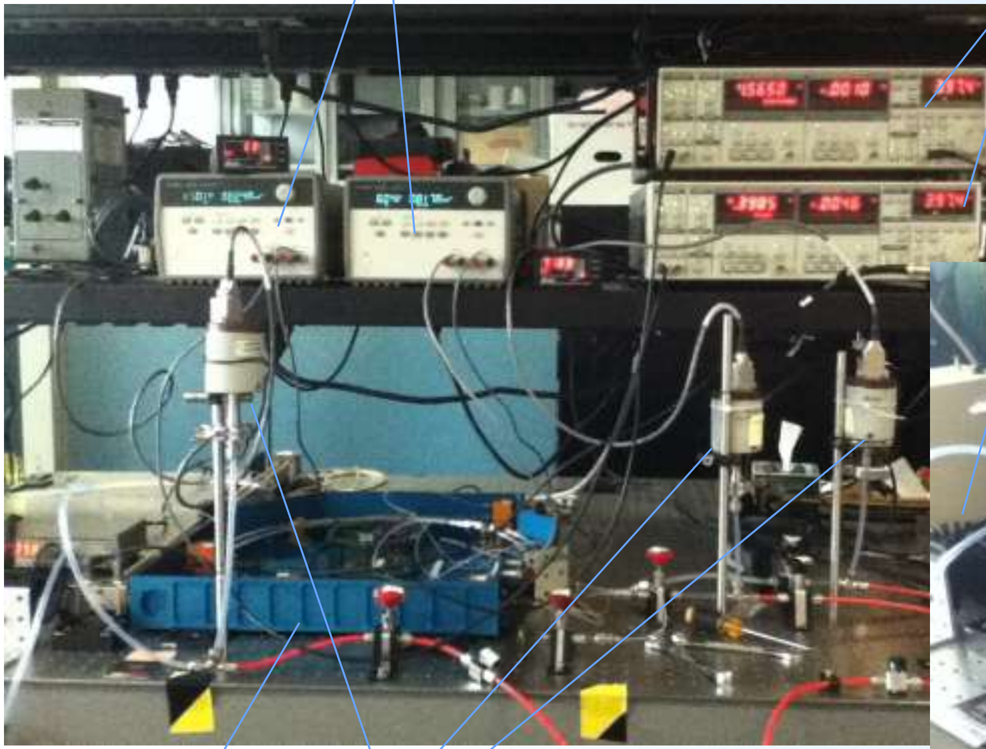


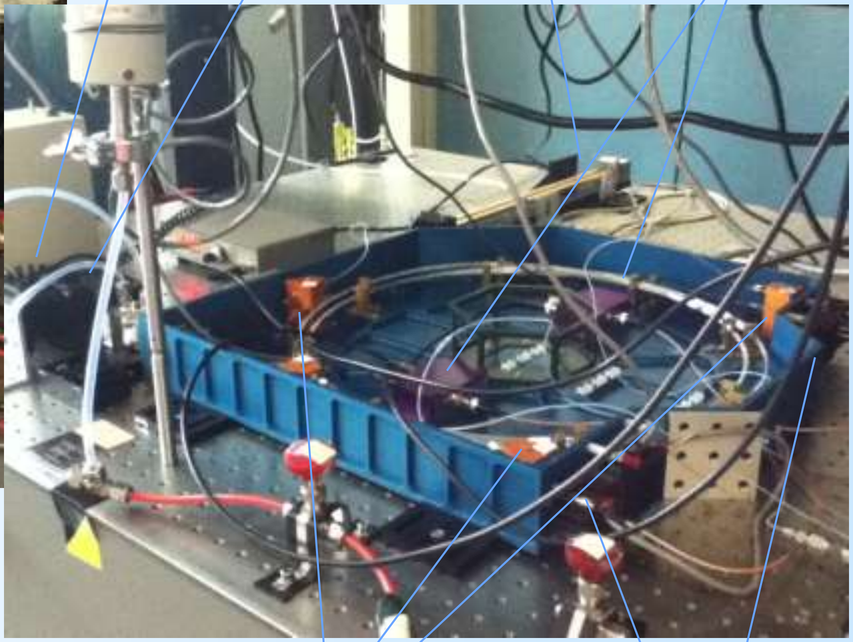
Single gas module



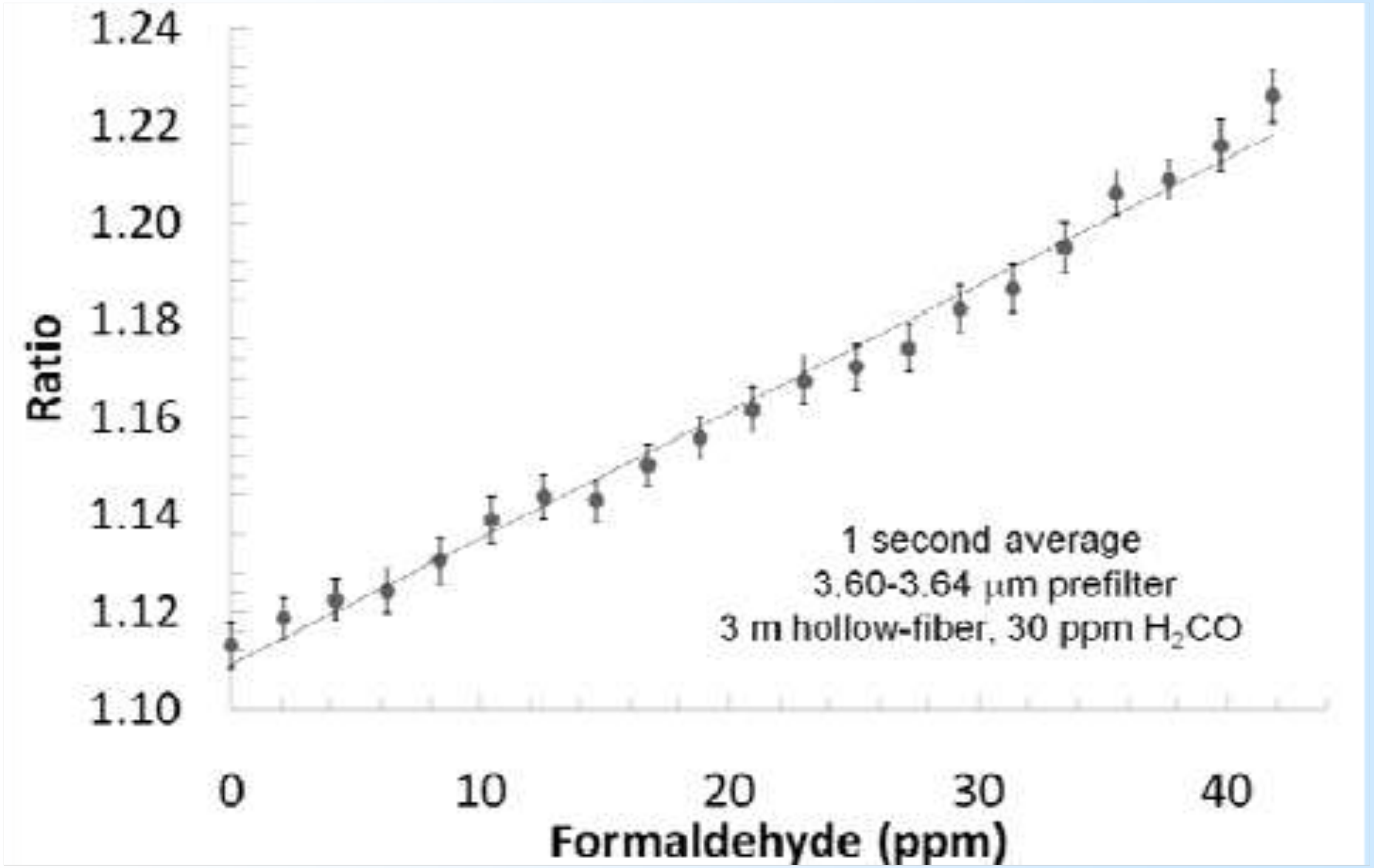


Current Lab Set-up



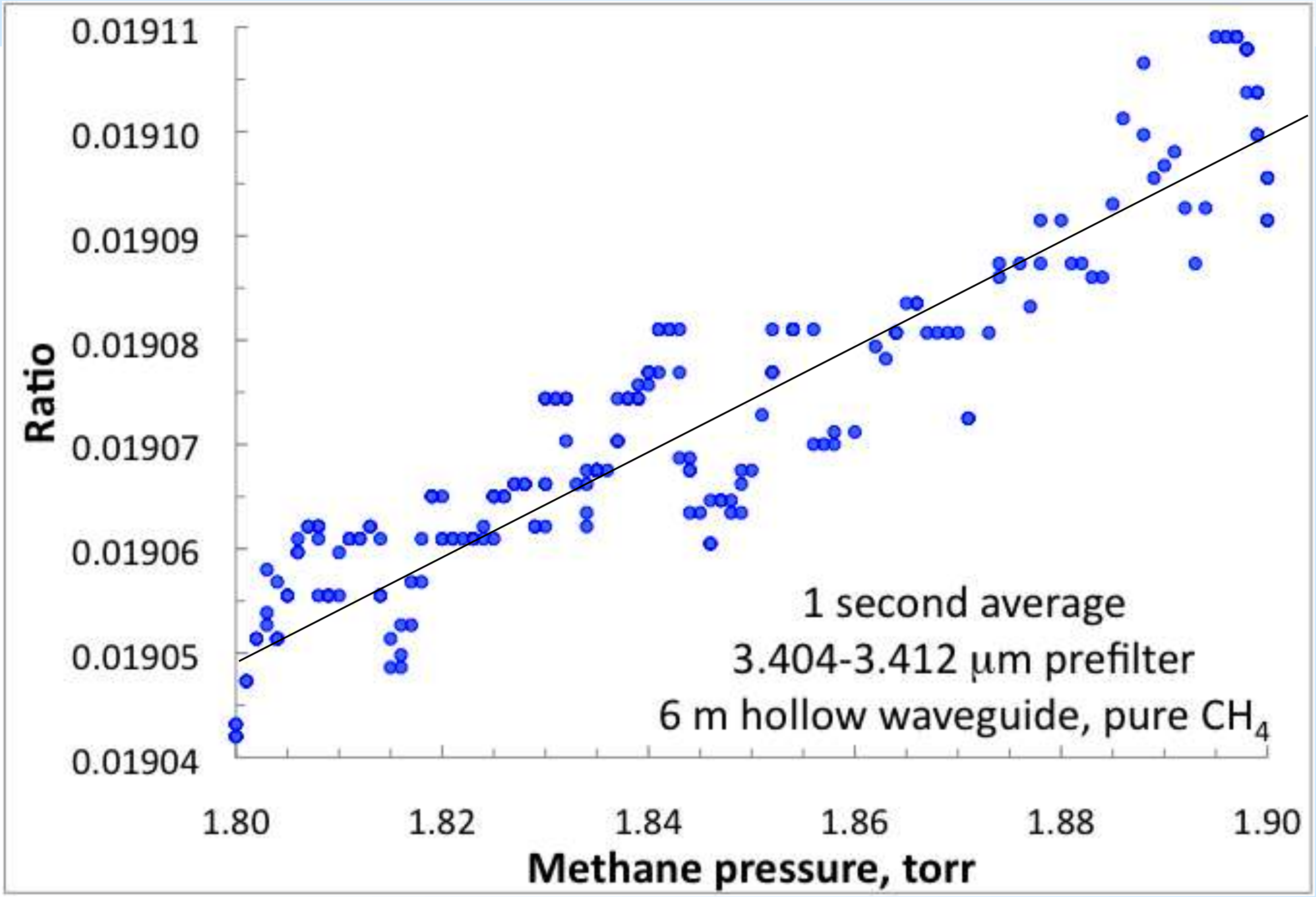


Formaldehyde results



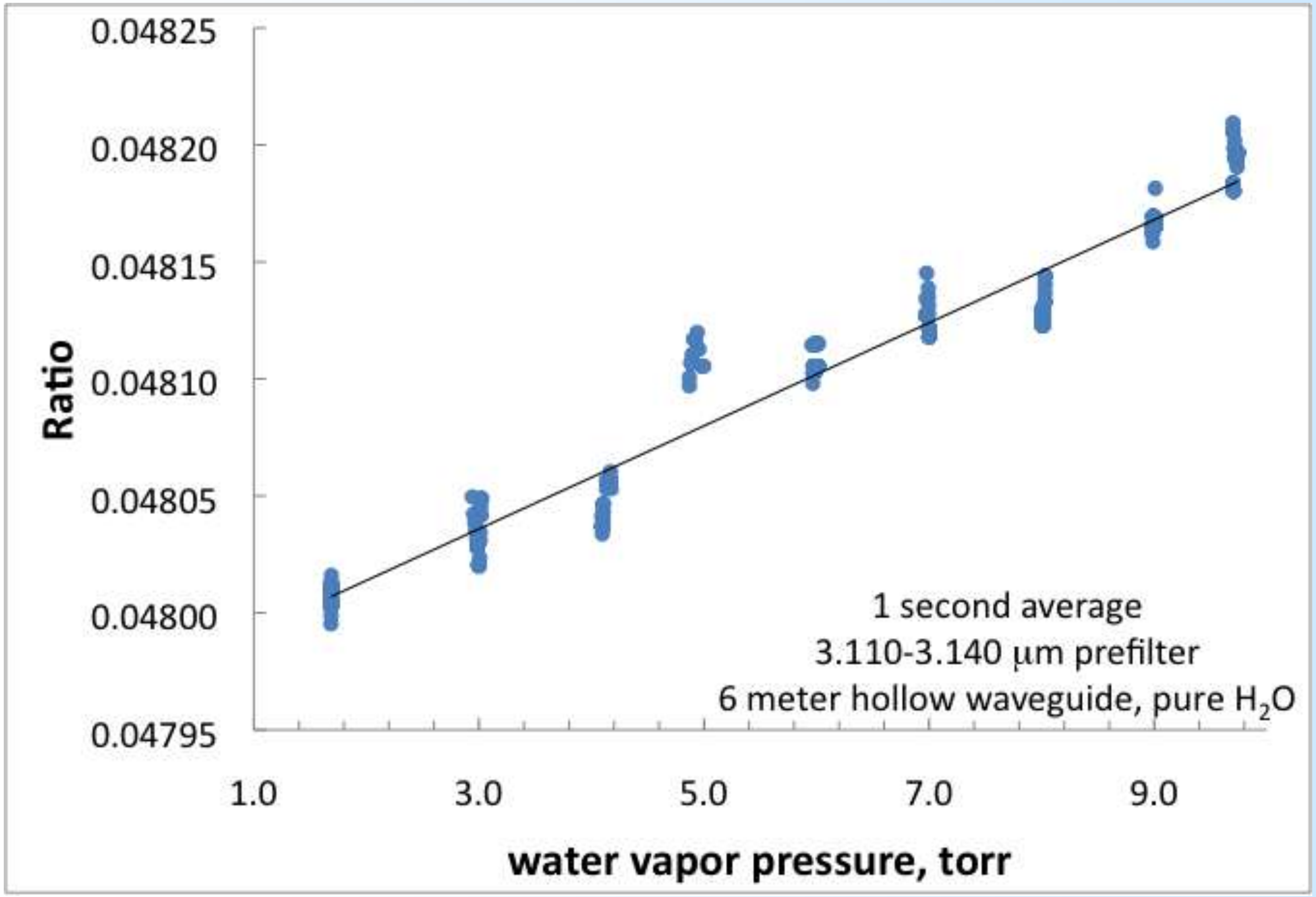
Equivalent to 30 ppb in Martian atmosphere

Methane results



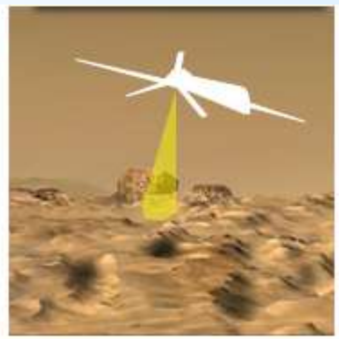
Equivalent to 0.5 ppm in Martian atmosphere

Water vapor

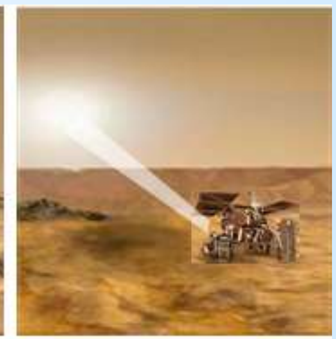

0.04825
0.04820
0.04815
0.04810
0.04805
0.04800
0.04795
Ratio
1.0
3.0
5.0
7.0
9.0
water vapor pressure, torr
1 second average
3.110-3.140 μm prefilter
6 meter hollow waveguide, pure H2O

Potential Missions

Orbiter



Aircraft probe



Surface network

(February 2008) MEPAG (Mars Exploration Program Analysis Group) Mars Strategic Science Assessment Group presentation states that "trace gases (methane, and other hydrocarbons, halogen and sulfur species, etc.) are vitally important but are poorly characterized or undetected."

NASA Strategic Subgoal 3C, "Advance scientific knowledge of the origin and history of the solar system, the potential for life elsewhere, and the hazards and resources present as humans explore space."

Sensitivity Estimate

Simulation of performance of Mars orbiting version of instrument

- simulation generates a synthetic spectrum for reflected light containing spectral features for H_2CO, CH_4, and H_2O from the HITRAN database
- reflected solar flux signal received in the two channels of each sub-instrument (evacuated and gas-filled correlation cells) is then calculated for light that has passed through the Martian atmosphere, reflected off the surface, and passed back up to the spacecraft
- the total column of the species of interest is perturbed by 1% and the signals are recalculated
- compare the change in the ratio (filled cell to evacuated cell) caused by the perturbation to the detector noise of this ratio
- free parameters of the instrument design (filter bandpass, filter edge slopes, instrument FOV, etc.) are varied in an effort to maximize the response to the species measured
- careful selection of the prefilter bandpass is required because H_2CO, CH_4, and H_2O all have absorption features in the same regions. Water vapor is found throughout the 3.5 micron region, and formaldehyde and methane have features caused by the same C-H stretch.

Sensitivity Estimate Continued…

Assumptions

- 2 meter long, 1000 micron inner diameter hollow-core fiber gas correlation cell
- 92.8 degree sun-synchronous orbit from 400 km
- Horizontal sampling scale of 10 km x 10 km

Initial Results

For one second of averaging (3 km displacement along the satellite ground track), a detection limit of 1 ppbv is possible for formaldehyde, with slightly better than 1 ppbv for methane 92.8 degree sun-synchronous orbit from 400 km

Atmospheric species	Methane (CH_4), water vapor (H_2O), deuterated water vapor (HDO), ethane (C_2H_6), formaldehyde (CH_2O), nitrous oxide (N_2O), hydrogen sulfide (H_2S), methanol (CH_3OH), sulfur dioxide (SO_2), carbon dioxide (CO_2), oxygen (O_2)	
Instrument field of view	10 km x 10 km footprint	
Sample Detection limits	Methane (CH_4), formaldehyde (CH_2O)	~ 1 ppb
	Water vapor	<1 ppm
Mass estimate	~9kg (for a 4 module instrument)	
Volume estimate	<0.01 m^3	
Power estimate	12 Watts (depending on bus temperature and need for TEC cooling)	
Data rate estimate	<20 Mbits/day	

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Comparisons

	Mars	Earth
Surface pressure	0.6-1 kPa	101 kPa
Solar Irradiance	~590 W/m^2	~1350 W/m^2
Albedo	0.15	0.367
Surface density	~0.020 kg/m^3	1.217 kg/m^3
Atmospheric Scale height	11.1 km	8.5 km
Total mass of atmosphere	~2.5 x 10^{16} kg	5.1 x 10^{18} kg
Average temperature	~210 K (-63 C)	288 K (15 C)
Wind speeds	2-10 m/s (up to 30 in dust storms)	0 to 100 m/s
Mean molecular weight	43.34 g/mole	28.97 g/mole

Atmospheric Composition

Mars

Carbon Dioxide (CO_2) - 95.32%
Nitrogen (N_2) - 2.7%
Argon (Ar) - 1.6%
Oxygen (O_2) - 0.13%
Carbon Monoxide (CO) - 0.08%
Water (H_2O) – 210 ppm
Nitrogen Oxide (NO) – 100 ppm
Neon (Ne) - 2.5 ppm
Hydrogen-Deuterium-Oxygen (HDO) - 0.85 ppm;
Krypton (Kr) - 0.3 ppm
Xenon (Xe) - 0.08 ppm

Earth

Nitrogen (N_2) – 78.08%
Oxygen (O_2) – 20.95%
Argon (Ar) – 9340 ppm
Carbon Dioxide (CO_2) - 380 ppm
Neon (Ne) - 18.18 ppm
Helium (He) - 5.24 ppm
Methane (CH_4) - 1.7 ppm
Krypton (Kr) - 1.14 ppm
Hydrogen (H_2) - 0.55 ppm

Water vapor (H_2O) - ~1% variable