Methane Sensor for Mars (MSM)

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Abstract

Methane Sensor for Mars (MSM), on-board Mars Orbiter Mission (MOM) is a differential radiometer based on FPE (Fabry-Perot Etalon) filter which measures column density of methane in the Martian atmosphere. It is the first FPE sensor ever flown to space. As MOM mission completes its first 100 orbits around Mars, MSM has already collected large volume of data completely covering the low latitude regions from 30°S to 40°N.

1. Introduction

Mars is a terrestrial planet which lies very close to the habitable zone of our solar system. Like Earth, Mars has an atmosphere, hydrosphere, cryosphere and lithosphere. Thermal environment of Mars is believed to be suitable for the development and evolution of life forms. So, when methane was first discovered on Mars in 2003 by Mars Express Mission of European Space Agency, it generated a lot of interest among scientific community as methane is a potential sign of primitive life. Alternatively, the presence of methane in the Martian atmosphere can also be explained in terms of geological activities.

Since 2003, four research groups have measured methane in the Mars atmosphere, either through terrestrial or satellite based observations.[1-5] The measured concentration was between 5-100ppb. It is found that methane concentration undergoes very rapid temporal and spatial variations with a life time of less than one year. Even though, it is very clear that methane is continuously generated and annihilated on Mars, the processes (biotic or abiotic) by which it is happening is still unknown.

MSM (Methane Sensor for Mars) on-board ISRO/India's Mars Orbiter Mission (MOM) is designed to measure total column of methane in the Martian atmosphere. It is a differential radiometer based on Fabry-Perot Etalon (FPE) Filters with a measurement accuracy of the order of few ppbs (parts per billion). MSM can map the sources and sinks of methane by scanning the full Martian disc from the apogee positions of Mars Orbiter. By correlating the temporal and spatial variations of methane with other geophysical parameters, it may be possible to find out more about the processes, biotic or abiotic which determine the dynamics of methane cycle within the Martian atmosphere.

2. Measurement principle

MSM is a differential radiometer which makes use of FPE filters to measure solar radiation reflected from planetary surface in the SWIR (Short Wave Infra Red) region. FPE is an optical filter that transmits light at extremely narrow, well defined spectral bands which are evenly spaced in the frequency domain. Figure-1A gives the schematic of an FPE filter. It consists of two parallel reflecting surfaces facing each other. When light falls on it from one side it undergoes multiple reflections between the reflecting inner surfaces and emerges from the other side. Depending on the number of reflections that the ray has undergone, its path length /phase changes. Rays having different phases interfere to generate intensity maxima at frequencies at which path difference is an integral multiple of wavelength. So, FPE filter basically transmits light at regular intervals of frequency. Transmittance of FPE is given by,

$$T = \frac{1}{1 + \mathrm{F}\sin^2(\frac{\delta}{2})} \quad \ldots\ldots\ldots\ldots (1)$$

where

$$F = \frac{4\mathrm{R}}{(1 - 4R)^2}$$

$$\delta = \frac{4\pi\, \mathrm{nd}\cos\theta}{\lambda}$$

d is the separation between the reflecting surfaces, R is the reflectance, θ is the angle of incidence, λ is the wavelength and n is the refractive index of the spacer medium between the reflecting surfaces.

Two parameters which characterize a FPE filter are (1) FSR (Free Spectral Range), the spectral separation between subsequent transmission peaks and (2) FWHM (Full Width at Half Maximum) or band width of transmission bands. It can be shown that,

$$FSR = \frac{1}{2\,\mathrm{n}\,\mathrm{d}} \quad \ldots\ldots\ldots\ldots(2)$$

So, FSR can be modified by varying the refractive index of the spacer medium or the separation between reflecting surfaces. Similarly, FWHM can be varied by varying the reflectance. More the reflectance narrower the transmission peaks. Fgure1B shows estimated transmission of an FPE for the design parameters mentioned therein.

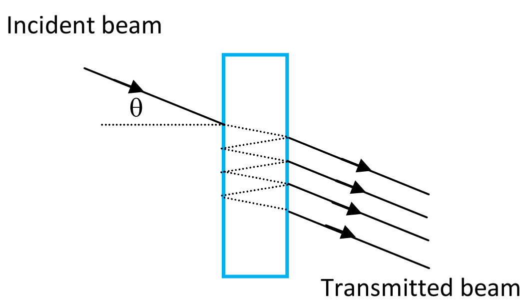

FIG-1A: Schematic of FPE filter

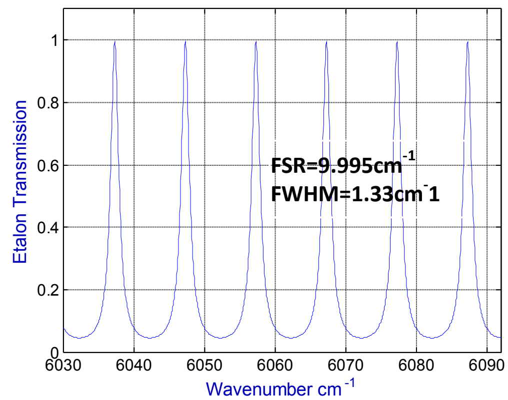

FIG-1B: Transmittance of FPE filter estimated for the design paramereters d=0.03cm, n=1.44 and R=0.85

It may be noted that if absorption lines of the gas to be measured are evenly spaced in frequency space, we can design an FPE sensor which can measure absorption simultaneously at many wavelength positions. Compared to broad band sensors, etalon sensors are very much sensitive to variation in gas concentration since they measure radiation only at those wavelengths where gaseous absorption is large.

Absorption spectrum of methane (CH_4) in the NIR-LWIR region is due to the vibrational and rotational transitions. CH_4 is a non-linear molecule having tetrahedral structure as shown in Figure-2 and does not have any permanent dipole moment. Since it is a non linear molecule, it has 3n-6=9 vibration modes (where n=5 is the number of atoms). Of these, three modes are IR inactive. The remaining modes are triply degenerate with fundamental frequencies centered at $\nu 1=3156.8cm^{-1}$ and $\nu 2=1367.4cm^{-1}$. Apart from vibrational states the molecule has rotational levels. Since energies of rotational levels are relatively small they are occupied even at low temperatures. So vibration-rotation transitions of gases usually consist of thousands of densely packed line intensities. Figure-3 shows the line intensity spectrum of methane in the 1000-10000cm^{-1} region which has more than one lakh lines.

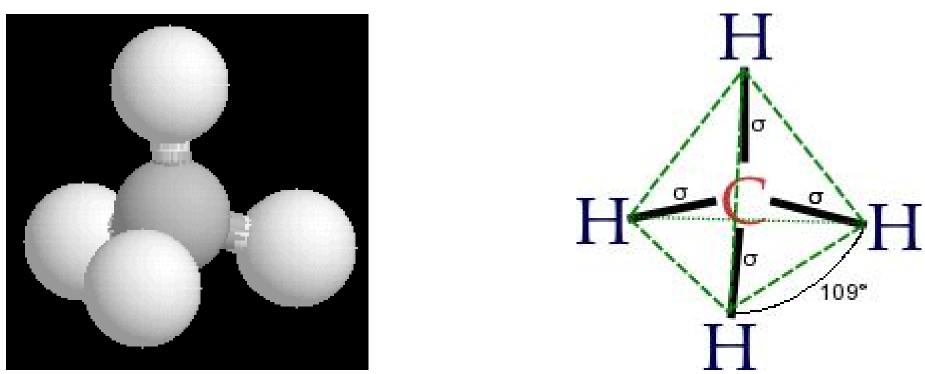

FIG-2: Structure of CH_4 molecule

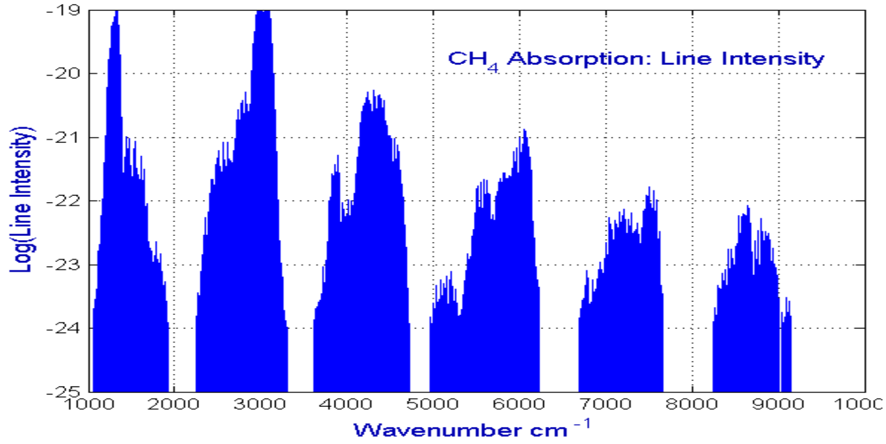

FIG. 3: Line intensities of CH_4 molecule (Source: HITRAN)

In principle, methane can be estimated by measuring radiance anywhere in the spectral region where absorption is significant. The main criteria for choosing an optimum spectral region for gas measurement are (1) absorption line intensities should be sufficiently large (2) absorption by other gas species should be negligible (3) availability and cost of suitable detectors and optical components for the wavelength region. Considering these aspects, a spectral region between 6010-6090cm^{-1} which has six prominent absorption lines is chosen for measurement. Separation between adjacent lines is ~10cm^{-1}. It may be noted that these lines are part of the second harmonic of the fundamental mode centered at 3156.8cm^{-1}. FPE of MSM is designed to measure radiance at these line positions.

Figure-4 gives the optical transmission of FPE filter of MSM (estimated from the design parameters) along with absorption lines of methane. As can be seen, transmission peaks of the filter coincide with the absorption lines of methane. Since radiation is measured only at line positions rather than over a wide spectral band, MSM is very sensitive to variations in gas concentration.

To retrieve gas concentration, the radiance measured by the sensor needs to be corrected for ground reflectance and atmospheric scattering. Conventionally, it is done by measuring radiance in a broad reference channel which is away from gaseous absorption band.[6,7] Since ground reflectance and atmospheric scattering depend on wavelength, it is not possible to correct the data fully. The new sensor design of MSM innovatively circumvents this problem by making use of another FPE filter in the reference channel with its transmission peaks falling in midway between gaseous absorption lines rather than outside the band. Therefore methane absorption in the reference channel is very small (<5% compared to methane channel) whereas ground reflectance and atmospheric scattering remains practically same. Red dotted line in Figure-4 also gives spectral transmittance of reference channel FPE estimated based on design parameters.

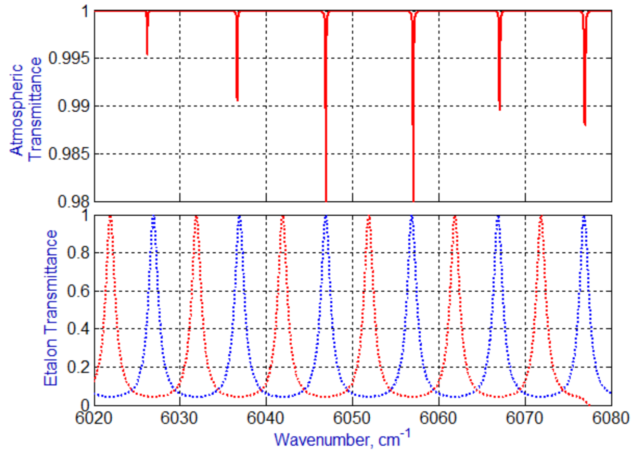

FIG.4: Spectral transmittance of FPEs of methane (blue dotted line) and reference channels (red dotted line) simulated based on design parameters. Red solid curve give atmospheric transmittance due to CH_4 absorption.

3. MSM Configuration

Figure-5 gives the optical configuration of MSM. Fore-optics collects radiance from the scene and focuses it onto a field-stop which limits the FOV (Field Of View) of the sensor to reduce stray radiation. Diverging beam from the field stop is collimated and then divided into two parts by a beam splitter. One part of the beam transmits through FPE filter of methane channel whereas the other part transmits through FPE filter of reference channel and then is focused onto respective focal planes.

FPE filters used in methane and reference channels are identical. But, FPE filter of reference channel is tilted by ~2° with respect to the optical axis so that its transmission peaks are shifted by ~5cm^{-1}, thereby falling mid-way between methane absorption lines. Positions of FPE transmission peaks vary with temperature and angle of incidence. Temperature of FPE is maintained within 0.1K so that frequency shift is less than 0.005cm^{-1}. Similarly, mechanical configuration of the system ensures that alignment stability of etalon is better than 0.01°.

Focal plane assemblies of methane and reference channels consist of eight element InGaAs (Indium Gallium Arsenide) photo diode. So, MSM has eight methane channels and eight reference channels. Detector arrays are aligned in the cross-track direction. Each pixel of methane channel is co-registered with corresponding pixel of reference channel so that they will be looking at the same ground scene. Note that for a non-uniform scene, registration error will cause differential signals which may be wrongly interpreted as methane absorption. So registration error should be as small as possible.

Expected variation in radiance signal due to methane absorption is of the order of 0.005% for 10ppb column density. Measurement of such a small variation requires very high SNR (Signal to Noise Ratio) performance. Also, radiometric resolution in terms of digitization bits should also be high. Readout and processing electronics of MSM has been designed to cater to these requirements.

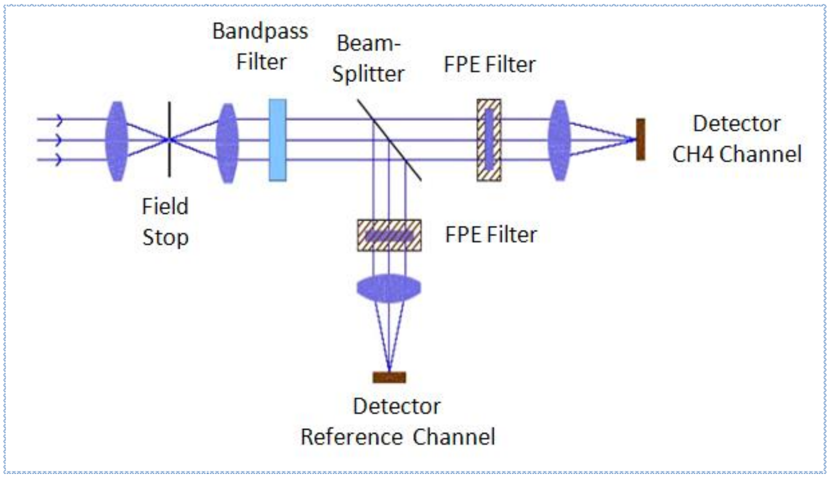

FIG. 5: Optical configuration of MSM

The analog current signal from the photo-diode is converted into a voltage signal, amplified and digitized. The image data having 20 bit resolution is transmitted to the ground station along with other housekeeping parameters. Measured SNR of MSM is better than7000 in all channels at saturation level. Figure-6 shows the flight model of MSM while Table-1 gives its salient features.

4. Post-Launch Performance

Mars Orbiter spacecraft was launched on 5th Nov, 2013. During the long cruise of MOM towards Mars, health parameters of MSM were regularly checked and were found within specifications. MOM was inserted into the Mars orbit on 27th September 2014 and the regular imaging sessions started during the second orbit itself. On 21st June 2015, when MOM completed its 100th orbit around the red planet, MSM had already acquired large volume of data completely covering the low latitude regions. Analysis of data is going on. Figure-7 gives the reflectance map of Mars in the 1.65um region generated from MSM data.

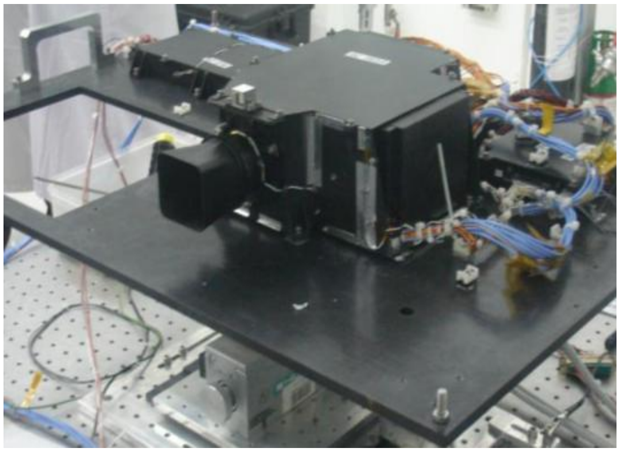

FIG. 6: Flight model of MSM

Optics	Aperture: 5cm, F-number: 1 IFOV: 1.7 milli radians
Spectral Region	6030-6090cm^{-1}
Spectral Resolution	1.4cm^{-1} (0.37nm)
FPE Filters	FSR: 9.995 cm^{-1} , FWHM: 1.4cm^{-1}
Detectors	InGaAs, 85µm pixel, 8 elements
Integration Time	0.25/0.5/1/2msec (selectable)
Digitization	20 bits
Signal to Noise Ratio	> 7000 @ saturation
Methane Sensitivity	38-60 ppb for 10sec intégration
Size	426mm x 355mm x 118mm
Mass	2.95kg
Power	7W

Table 1: Salient features of MSM

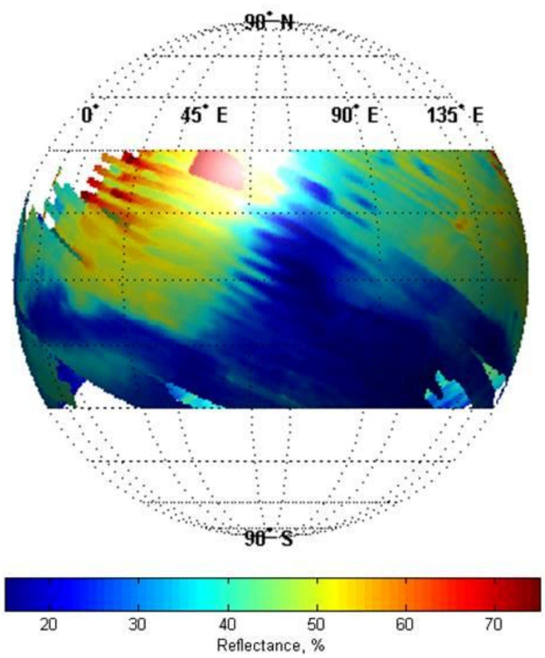

Figure-7 Reflectance map of Mars in the 1.65um region generated from MSM data.

5. Conclusions

Methane Sensor for Mars on-board Mars Orbiter Mission is the first Fabry-Perot Etalon based sensor ever sent to space. The payload has already acquired large volume of data completely covering the low latitude regions from 30S to 30N. The radiometric quality of the data is found to be satisfactory.

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V. References

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