SYNERGISTIC ATMOSPHERIC RETRIEVALS : MARTIAN CO AS A TEST-CASE.

S. Robert, *Royal Belgian Institute for Space Aeronomy, Brussels, Belgium (severine.robert@aeronomie.be)*, **F. Montmessin,** *LATMOS, Guyancourt, France*, **S. Ferron,** *ACRI-ST, Sophia-Antipolis, France*, **F. Altieri, G. Bellucci, A. Geminale, M. Giuranna, G. Sindoni,** *Istituto di Astrofisica e Planetologia Spaziali, Rome, Italy*, **S. Aoki, A. Piccialli, A.C. Vandaele,** *Royal Belgian Institute for Space Aeronomy, Brussels, Belgium*.

Introduction

Since 2004, the European mission, Mars Express [1], has delivered a tremendous quantity of data concerning the surface and the atmosphere of Mars. Hopefully so will the ExoMars Trace Gas Orbiter [2] (EMTGO) which will be inserted into orbit around Mars in October 2016. The datasets are generally studied separately and that is a necessary first step. However, because each of the spectral regions and geometries has its advantages and disadvantages, the combination of different types of measurements in a synergistic way enables us to better exploit the available data and increase the science return. Carbon monoxide was used as a test-case in both studies we will present here. CO is a non-condensable gas present in the atmosphere of Mars, varying from 300 to 1500 parts per million in volume mixing ratios, depending on the season. The remote sensing of CO can be performed in different spectral domains and with different geometries of observation.

This presentation is two-folded:

1. Simulated spectra based on the characteristics of the two InfraRed instruments onboard EMTGO were used in a theoretical study that enabled us to demonstrate the usefulness of synergistic retrievals and pave the way to more collaborative studies [3].

2. The tools we developed during the first step were confronted to real data in a study associating PFS and OMEGA data, both instruments onboard Mars Express. Preliminary results of this work will be discussed.

Synergistic retrievals on simulated data

To prove the validity of the synergistic concept, we performed a theoretical study based on the performances expected from two infrared instruments on board EMTGO: NOMAD [4] and ACS [5]. Therefore, a synthetic dataset of spectra of the Martian atmosphere has been created. Scenarios have been defined varying sites on the planet, solar longitudes, CO and CH_4 volume mixing ratios, aerosol loadings, instrument types, observation modes and solar zenith angles for nadir and tangent heights for solar occulations. Two instrument types have been defined: one is a grating spectrometer with an Acousto-Optical Tunable Filter (GA) working between 2.2 and 4.4 microns and the other is a Fourier Transform spectrometer (FTS) measuring on a broader range, from 2 to 25 microns. Relative Signal-to-Noise ratio, spectral sampling and resolution have been estimated according to the performances planned for the EMTGO mission and are given in the Table 1. We consider that these two instruments can perform solar occultations (SO) and nadir observations.

Instrument	GA instrument		FTS instrument	
Geometry	nadir	SO	nadir	SO
Type of instrument	AOTF + echelle spectrometer		Fourier transform spectrometer	
ILS	Gaussian		sinc	
Spectral resolution (cm^{-1})	0.30	0.15	1.6	0.20
Instantaneous spectral coverage	24 cm^{-1}	22 cm^{-1}	Whole range	
Lower limit	2500 cm^{-1}		400 cm^{-1}	
Upper limit	4600 cm^{-1}		5000 cm^{-1}	
Signal-to-Noise ratio	1000	4000	500	1000

Table 1: Instruments' channels considered in the theoretical study.

To perform the retrievals, we selected different spectral windows for each instrument and each geometry of observation. These were used as such in the case of non synergistic retrievals. In the cases of synergies, we used the same spectral ranges but in combination:

- For the Level 1 /Level 1 (L1/L1) synergy, selected spectral windows were used simultaneously. The volume mixing ratios of 4 species (and the surface temperature in the case of nadir) were retrieved thanks to the information available in these spectral ranges of both instruments' channels.

- For the Level 2 /Level 1 (L2/L1) synergy, CO_2, H_2O (and the surface temperature in the case of nadir) were retrieved in the first step using the FTS' selected spectral windows. The results of this first run were used as inputs in the second step consisting in retrieveing CO and CH_4 vmr using the spectra of the GA instrument.

Instrument specifications, wavenumber range, observation geometry and state of the atmosphere are given as input elements. Spectra were simulated according to the various scenarios selected and given in the Table 2. To obtain a statistical sample, we randomly added noise to these simulated spectra. Batch of 50 spectra were created to perform the retrievals on, using ASIMUT-ALVL, an home-made Radiative Transfer code [6].

Location	Arabia Terra 0-40°N ; 0-44°E
L_S (°)	30-60 ;120-150 ; 210-240 ; 300-330
Molecules to simulate/ retrieve CO content (ppmv) CH_4 content (ppbv)	 CO_2, H_2O, CH_4, CO, O_3 low (321) / high (1362) low (10) / high (60)
[nadir] Solar zenith angles Emission temperature of the ground for the different seasons (T_{surf} in K)	30° 212.23 ; 216.27 ; 211.71 ; 204.08
[SO] Tangent heights (in km above the surface) Blackbody temperature the incoming solar spectrum	1, 3, 5, 10, 15, 20, 25, 27.5, 30, 32.5, 35, 37.5, 40, 45 5780 K

Table 2: Summary of the specifications of the selected geophysical scenrios to be simulated. The seasons are given for the Northern hemisphere. the surface temperatures are from GEM-Mars [7].

In NADIR

The CO retrievals with the GA instrument were performed using the 2-0 band in a spectral window of 35 cm^{-1} width, i.e. between 4267 and 4302 cm^{-1}. The CO retrievals with the FTS were done using the 1-0 band in a spectral window 250 cm^{-1} wide, between 2000 and 2250 cm^{-1}. A number of 50 noisy spectra was used in each scenario. They give similar results, as can be seen in Fig.1. The distribution of the results are represented by the coloured markers in bin of 1 or 2 ppmv. Errors are also given, as dotted horizontal coloured lines in the figures. The results are shown for all 4 L_S periods. There is no significant seasonal trends. The retrievals using the GA instrument are centered around the black vertical line, i.e. the true solution, within the error bars which reach 0.3% and 0.7% in the case of high and low VMR respectively.

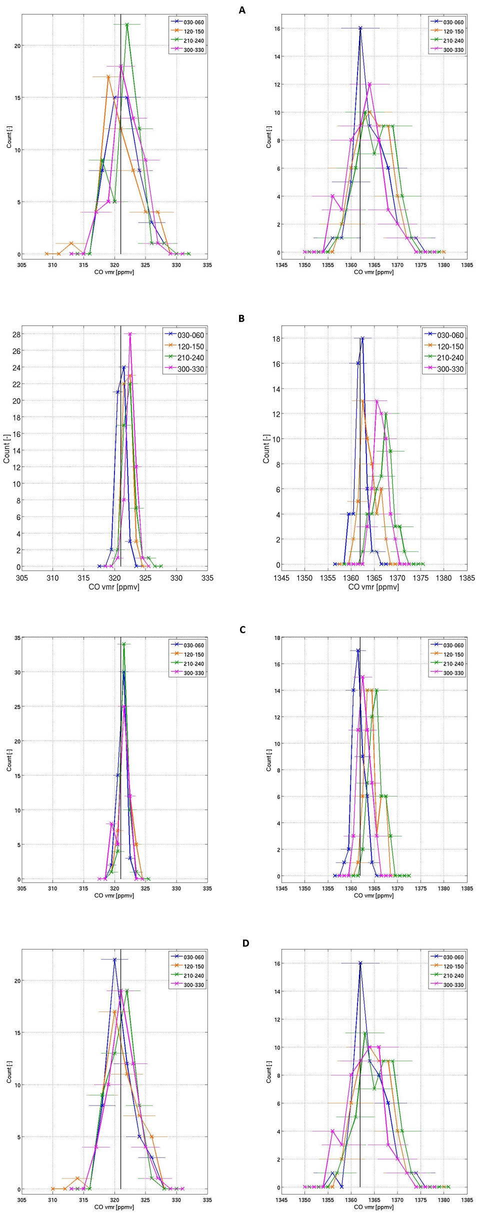

Figure 1: Statistical distribution of the 50 retrievals of CO in nadir in **(A)** GA only retrievals, **(B)** FTS only retrievals, **(C)** L1/L1 synergy case and **(D)** L2/L1 synergy case. The four different Ls periods are indicated in different colors. The a priori value was 841.5 ppmv in all cases and is not represented on the plots. All results within 1 or 2 ppmv are binned together. The black vertical line on each plot represents the GEM value expected to be retrieved, with low VMR (321 ppmv) on the left and a high VMR (1362 ppmv) on the right.

The synergy L1/L1 benefits from both spectra and from the information contained in both bands of CO measured by the instruments. This is confirmed by the retrieved VMR values and their a posteriori uncertainties. The L1/L1 synergy profile is the closest to the true solution and presents the smallest error bars at each season.

In Solar Occultation

14 spectra were used for the solar occultation retrievals. They span altitudes from 1 up to 45 km above the surface. The 2-0 band was used to retrieve CO, using a spectral range from 4248 to 4305 cm^{-1}. 250 cm^{-1} were used to perform the retrievals of CO vmr using the FTS, from 2000 to 2250 cm^{-1} targeting the fundamental band, 1-0. 10 noisy spectra were produced and used as dataset to perform the retrievals. The results are shown on Fig.2.

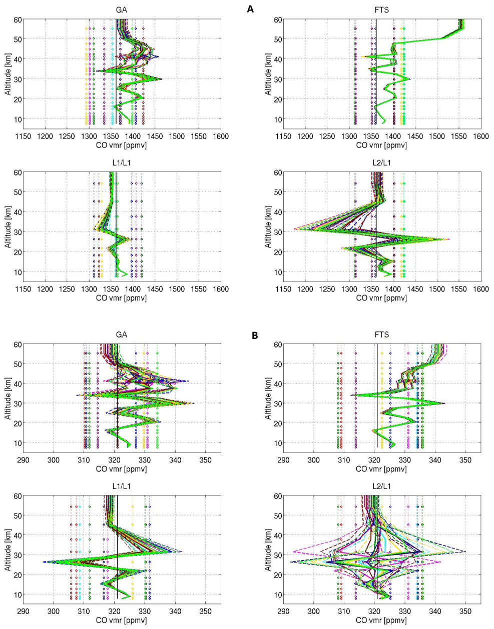

Figure 2: 10 vertical profiles in the case Ls=30-60° in **(A)** high and **(B)** low VMR conditions and in solar occultation. Upper left panel: GA instrument alone Upper right panel: FTS instrument alone Lower left panel: L1/L1 synergy Lower right panel: L2/L1 synergy. The expected true solution is a constant 1362 ppmv or 321 ppmv volume mixing ratio, in black. One single colour represents one retrieval. The solid line shows the retrieved profile, the dashed line with markers represents the a priori and the uncertainty is given in dotted line.

Averaging Kernels and Degree of Freedom for Signal have been compared in each case as well. Again, the synergy L1/L1 benefits from both spectra and from the information contained in both bands of CO measured by the instruments.

Synergistic retrievals on experimental data

In a second phase, we focused on experimental data, this time using the datasets of two infrared instruments on board Mars Express, OMEGA [8] and PFS [9]. We selected datasets in the Hellas Planitia region (30-55°S ; 45-90° E) during Southern winter. Thess conditions should be advantageous when aiming for a successful retrieval of CO. Therefore, we chose to test the orbit 1186, as it was used by Encrenaz et al. [10] and Sindoni et al. [11] and as a high abundance of CO has been retrieved from this orbit in both studies. Two channels of OMEGA and two of PFS were taken into account in order to retrieve surface temperature, CO_2, H_2O and CO abundances and if possible, surface emissivity and aerosols contents. The characteristics of the channels are given in Table 3.

Instrument	OMEGA		PFS	
Geometry	nadir		nadir	
Type of instrument	Mapping spectrometer		Fourier transform spectrometer	
ILS	Gaussian		PFS ILS	
Channel	SWIR-C	SWIR-L	SWC	LWC
Spectral range (μm)	0.93-2.69	2.52-5.09	1.2-5	5-45
Spectral resolution	14 nm	23 nm	1.3 cm^{-1}	1.3 cm^{-1}
Signal-to-Noise ratio	>100	> 100	100	100

Table 3: Characteristics of the instruments' channels.

The OMEGA data were downloaded on the Planetary Science Archive FTP. An algorithm of data validation was written based on some papers of the OMEGA literature [12, 13, 14]. Criteria were defined and the dataset was validated. Among others, the cloud index was checked.

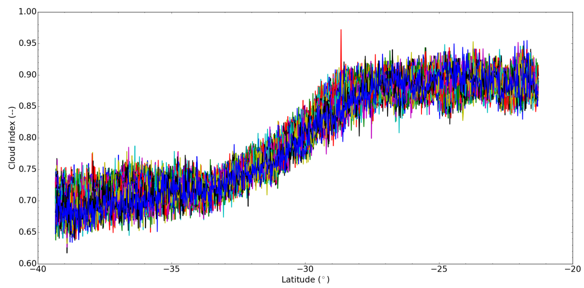

Figure 3: Cloud index for the 63488 spectels of OMEGA in orbit 1186.

As defined in Langevin et al. [12], the cloud index is the ratio between the reflectance factor measured at two different wavelengths (3.40 μm and 3.52 μm). If this index is above 0.8, we can assume that there is no cloud present in the atmosphere at the time of observation. The cloud index in function of latitude for orbit 1186_4 is shown in Fig.3. In this case, 33727 spectels were removed from the dataset.

Up to date validated data of PFS' channels were formatted in one HDF5 file in order to perform the retrievals with ASIMUT-ALVL [6].

Modifications to ASIMUT-ALVL have been implemented to treat OMEGA and PFS data separately and altogether. Synergies will be defined properly, as will the diagnostic tools used as to claim a successful retrieval.

Acknowledgements

The research was performed as part of the "Interuniversity Attraction Poles" programme financed by the Belgian government (Planet TOPERS) and a BRAIN research grant BR/143/A2/SCOOP. The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under the grant agreement no. 607177 CrossDrive and from the European Union's Horizon 2020 Programme (H2020-Compet-08-2014) under grant agreement UPWARDS-633127.

References

[1] A. Chicarro et al. *Eur. Space Agency Spec. Publ.*, 1240:3–13, 2004.

[2] J. Vago et al. *Solar System Research*, 49(7):518–528, 2015.

[3] S. Robert et al. *Journal of Quantitative Spectroscopy and Radiative Transfer (in revision)*.

[4] A.C. Vandaele et al. *Planetary and Space Science*, 119:233–249, 2015.

[5] O.I. Korablev et al. *Solar System Research*, 49(7):529–537, 2015.

[6] A.C. Vandaele et al. *Journal of Geophysical Research*, 113:E00B23, 2008.

[7] F. Daerden et al. *Geophysical Research Letters*, 42(18):7319–7326, 2015.

[8] J.-P. Bibring et al. *Eur. Space Agency Spec. Publ.*, 1240:37–49, 2004.

[9] V. Formisano et al. *Eur. Space Agency Spec. Publ.*, 1240:71–94, 2004.

[10] Th. Encrenaz et al. *Astronomy & Astrophysics*, 459:265–270, 2006.

[11] G. Sindoni et al. *Planetary and Space Science*, 59:149–162, 2011.

[12] Y. Langevin et al. *Journal of Geophysical Research*, 112:E08S12, 2007.

[13] A. Ody. *Dépouillement et interprétation des données spatiales d'imagerie hyperspectrale de Mars (OMEGA/MEx) : Evolution volcanique de la surface de Mars.* PhD thesis, Université Paris Sud - Paris XI, 2012.

[14] J. Audouard. *Propriétés thermo-physiques et hydratation de la surface de Mars.* PhD thesis, Université Paris Sud - Paris XI, 2014.