SIROCCO - Synergetic SWIR and IR retrievals of near-surface concentrations of CH4 and CO for Earth and Planetary atmospheres

Executive summary of ESA study contract n° 4000107088 - Final version

NOVELTIS

BIRA-IASB aeronomie.be iaps SRON ULB UNIVERSITÉ LIBRE DE BRUXELLES, UNIVERSITÉ D'EUROPE

	Function	Name	Signature	Date
Prepared by	Project Engineers	SIROCCO Consortium	p.p.	17/12/14
Approved by	Project Manager & Atmosphere Level 2 Unit Coordinator	Carine PETIT		17/12/14
Verified by	Quality Manager	Cindy HORTALA	Po	17/12/14
Authorised by	Production Manager	Frédérique PONCHAUT		17/12/14
The report was written by:	NOVELTIS: Claude CAMY-PEYRET, Carine PETIT, Olivier LEZEAUX ULB: Pierre-François COHEUR, Lieven CLARISSE, Sophie BAUDUIN, Rosa ASTORECA IASB-BIRA : Ann Carine VANDAELE, Martine de MAZIERE, Séverine ROBERT, Evelyn de WACHTER SRON : Jochen LANDGRAF, Arno de LANGE, Ilse ABEN IAPS : Marco GIURANNA, Shoei AOKI, Alessandro ARONICA			

NOVELTIS
153 rue du Lac – 31670 Labège – France
Tél. : +33 (0)562 88 11 11 – Fax : +33 (0)562 88 11 12 – E-mail : noveltis@noveltis.fr

afaq QSE Qualité Sécurité Environnement AFNOR CERTIFICATION ISO 9001 - OHSAS 18001 ISO 14001

ESA STUDY CONTRACT REPORT No ESA Study Contract Report will be accepted unless this sheet is inserted at the beginning of each volume of the Report		
ESA CONTRACT **No 4000107088**	**SUBJECT** **SIROCCO - Synergetic SWIR and IR retrievals of near-surface concentrations of CH_4 and CO for Earth and Planetary atmospheres**	**CONTRACTOR** **NOVELTIS**
*** ESA CR ( ) No**	**No of Volumes: 1** **This is volume No:1**	**CONTRACTOR'S REFERENCE** **NOV-7132-NT-4006** **Ed. 1 – Rev. 0**

ABSTRACT:

The SIROCCO study was performed under ESA guidance by a consortium led by NOVELTIS and including four partners: ULB (Belgium), IASB-BIRA (Belgium), SRON (Netherlands) and IAPS (Italy). The goal of the study was to review in a multidisciplinary context (Earth Observation and Planetary Science) the status of existing retrieval algorithms and to extend their capabilities when applied to remote sensing data collected (or to be collected in the near future) by instruments in orbit around the planets Earth and Mars, with atmospheric carbon monoxide (CO) and methane (CH_4) as specific targets. A special focus was placed on deriving the near-surface concentrations of these two species (i.e. getting information on the atmospheric region called the planetary boundary layer or PBL). This specific objective is related to the detection and quantification of CO and CH_4 sources which are located at the surface, but which impact (through atmospheric transport and photochemical processes) the composition of the global atmosphere of these two sister planets of our solar system.

In a first task, the existing requirements, algorithms and data sets related to the retrieval of CO and CH_4 in the atmospheres of the two planets have been reviewed. In a second task, specific algorithms have been selected as effectively running on the premises of the 4 academic institutes participating in the study. The satellite data sets (Level 1 or L1 products i.e. spectra) available for testing the retrieval algorithms have been identified and collected (in some cases with a pre-processing as the spectral calibration of GOSAT spectra performed by NOVELTIS). The correlative measurements (other satellites, aircraft and ground-based stations) appropriate for validating the retrieved concentrations (Level 2 or L2 products) have also been chosen and collected. The third task was devoted to real retrievals and comparison exercises and have been separated by planet (Earth and Mars) and by type of retrieval (stand alone or non-synergistic and synergistic). Indeed for getting the best information on the full atmospheric profile of the target species (including their concentration in the PBL) it is expected that the combination (at the input of the inversion process) of L1 information originating from different sensors could be more efficient to generate reliable L2 products, than the separate generation of L2 products (total column, partial columns or sub-columns, profiles) with their strength and weaknesses. For example total column derived from nadir viewing instruments in the solar reflected shortwave infrared (SWIR) spectral region can be relatively precise since the light path through atmosphere is reaching the surface, but they do not provide vertical profile information. Conversely nadir viewing instruments operating in the thermal infrared regions have a sensitivity to the vertical distribution of the species because of the dependence of the received signal to the temperature profile, but their sensitivity is reduced in the PBL when the thermal contrast is low (i.e. when the surface temperature is equal to the temperature of the first atmospheric layer). Many of the possible spectral L1/L1 or L1/L2 synergies have been studied: L1(TIR,GOSAT)/L1(SWIR,GOSAT) or L1(TIR,IASI-NG)/L1(SWIR,S5) for Earth, L1(TIR,PFS)/L2(TIR T(z),PFS) or L1(SWIR,NOMAD)/L1(SWIR,ACS) for Mars. Remaining difficulties have been identified for CH_4 (with recommendations to solve them), but promising results have been obtained both for CO and CH_4 and for both planets benefiting from cross-fertilisation.

Names of the authors: NOVELTIS: Claude CAMY-PEYRET, Carine PETIT, Olivier LEZEAUX

ULB: Pierre-François COHEUR, Lieven CLARISSE, Sophie BAUDUIN, Rosa ASTORECA

IASB-BIRA: Ann Carine VANDAELE, Martine de MAZIERE, Séverine ROBERT, Evelyn de WACHTER

SRON: Jochen LANDGRAF, Arno de LANGE, Ilse ABEN

IAPS: Marco GIURANNA, Shoei AOKI, Alessandro ARONICA

** NAME OF ESA STUDY MANAGER Anne Grete STRAUME-LINDNER / Olivier WITASSE DIV: EOP-SMA / SRE-S	** ESA BUDGET HEADING General Studies Programme (GSP)

Distribution list

INTERNAL OF CONSORTIUM		EXTERNAL OF CONSORTIUM	
Name	**Company / Organisation**	**Name**	**Company / Organisation**
Documentation NOVELTIS		Anne Grete STRAUME-LINDNER	ESA / ESTEC
Richard BRU	NOVELTIS	Olivier WITASSE	ESA / ESTEC
Frédérique PONCHAUT	NOVELTIS		
Cindy HORTALA	NOVELTIS		
Pascal PRUNET	NOVELTIS		
Emmanuel DUFOUR	NOVELTIS		
Claude CAMY-PEYRET	NOVELTIS		
Olivier LEZEAUX	NOVELTIS		
Carine PETIT	NOVELTIS		
Pierre-François COHEUR	ULB		
Lieven CLARISSE	ULB		
Sophie BAUDUIN	ULB		
Rosa ASTORECA	ULB		
Ann Carine VANDAELE	IASB-BIRA		
Martine de MAZIERE	IASB-BIRA		
Séverine ROBERT	IASB-BIRA		
Evelyn de WACHTER	IASB-BRIA		
Jochen LANDGRAF	SRON		
Ilse ABEN	SRON		
Arno de LANGE	SRON		
Marco GUIRANNA	IAPS		
Shoei AOKI	IAPS		
Alessandro ARONICA	IAPS		

Document status

SIROCCO - Synergetic SWIR and IR retrievals of near-surface concentrations of CH4 and CO for Earth and Planetary atmospheres Executive summary of ESA study contract n° 4000107088 - Final version			
Issue	**Revision**	**Date**	**Reason for the revision**
0	1	28/11/14	Initial version
1	0	17/12/14	Final version

Modification status				
Issue	Rev	Status *	Modified pages	Reason for the modification
1	0	M	The whole document	Synthesis of the initial version from 40 to about 5 pages

* *I = Inserted D = deleted M = Modified*

References

	Reference	Title
[RD1]	TEC-EEP/2012.7/AS, Appendix 2 to ESA contract 4000107088	Statement of Work - Synergetic SWIR and IR retrievals of near-surface concentrations of CH_4 and CO for Earth and Planetary atmospheres.
[RD2]	SIROCCO consortium, NOV-7132-1155_v1.0, Technical, Management, Administrative and Financial Proposal, 27th April 2012.	Synergetic SWIR and IR retrievals of near-surface concentrations of CH_4 and CO for Earth and Planetary atmospheres.
[RD3]	SIROCCO consortium, NOV-7132-NT-1805_v1.2, Technical Note 1 of ESA study contract n° 4000107088/12/NL/AF, final version, 10th January 2014.	Synergetic SWIR and IR retrievals of near-surface concentrations of CH_4 and CO for Earth and Planetary atmospheres. Review of user requirements, sensors and retrieval schemes for near-surface CH_4 and CO concentrations.
[RD4]	SIROCCO consortium, NOV-7132-NT-2320_v1.0, Technical Note 2 of ESA study contract n° 4000107088/12/NL/AF, final version, 25th November 2013.	Synergetic SWIR and IR retrievals of near-surface concentrations of CH_4 and CO for Earth and Planetary atmospheres. Compilation of a test dataset.
[RD5]	SIROCCO consortium, NOV-7132-NT-2780_v1.2, Technical Note 3 of ESA study contract n° 4000107088/12/NL/AF, final version, 27th October 2014.	Synergetic SWIR and IR retrievals of near-surface concentrations of CH_4 and CO for Earth and Planetary atmospheres. Development of the combined SWIR and IR retrieval schemes - Earth
[RD6]	SIROCCO consortium, NOV-7132-NT-2781_v0.2, Technical Note 4 of ESA study contract n° 4000107088/12/NL/AF, final version, 15th April 2014.	Synergetic SWIR and IR retrievals of near-surface concentrations of CH_4 and CO for Earth and Planetary atmospheres. Development of the combined SWIR and IR retrieval schemes – Mars
[RD7]	SIROCCO consortium, NOV-7132-NT-4005_v0.1, Final Report of ESA study contract n° 4000107088/12/NL/AF, draft version, 28th November 2014.	Final report

Applicable documents

	Reference	Title
[AD1]	ESA Contract No 4000107088/12/NL/AF	SIROCCO - Synergetic SWIR and IR retrievals of near-surface concentrations of CH_4 and CO for Earth and Planetary atmospheres

Table of contents

1. Introduction to the SIROCCO project

The increase of direct (e.g. CH_4) and indirect (e.g. CO) greenhouse gases and polluting gases (e.g. CO) on Earth is predominantly responsible for global climate change. Adequate knowledge of sources and sinks of these gases and their climate and air quality feedbacks is a pre-requisite for a reliable prediction of climate on Earth. In spite of the recognised importance of this issue, our current understanding about sources and sinks of these gases is still inadequate. The context of these gases on Mars is very different as the quality and magnitude of remote sensing observations of the Martian atmosphere are limited, and hence the knowledge of its composition is still at a research stage.

Remote sensing of CO and CH_4 from space can be performed in different spectral regions (in particular the TIR and SWIR regions) and with different geometries (nadir, limb or solar occultation observations). Because each of these **spectral regions** and **viewing geometries** has its pros and cons, the scientific community is strongly hoping to be able to **combine** these types in a **synergistic** way in order to better exploit the available data**,** in particular to assess **near-surface processes.**

The challenge of the SIROCCO project was to better capture CO and CH_4 information **as close as possible to the associated surface sources**, for better understanding, quantifying and monitoring sources and sinks of these target species in the **Earth** and **Mars** atmospheres.

But clearly for both planets the full CO or CH_4 **profiles** are important (not only the near-surface concentrations) since the remote sensing signal is resulting from the various contributions of the different layers crossed by the line of sight (the full atmospheric column for nadir views or the layers above the lowest tangent height for solar occultation views). This is why the notions of **total column**, **partial column** or **sub-column in the surface boundary layer** are key concepts that appear all along the SIROCCO study. Also, as easily understandable, **atmospheric transport** (and the following **photochemical transformations**) of the species released near the planetary surface will determine the vertical profiles of the corresponding molecules (**CO** and **CH_4** in the SIROCCO study).

The goal of this 18 months study was to review in a multidisciplinary context (Earth Observation and Planetary Science) the status of existing retrieval algorithms and to extend their capabilities when applied to remote sensing data collected (or to be collected in the near future) by instruments in orbit around the planets Earth and Mars, with atmospheric carbon monoxide (CO) and methane (CH_4) as specific targets. A special focus was placed on deriving the near-surface concentrations of these two species (i.e. getting information on the atmospheric region called the Planetary Boundary Layer (PBL)). This specific objective is related to the detection and quantification of CO and CH_4 sources which are located at the surface, but which impact (through atmospheric transport and photochemical processes) the composition of the global atmosphere of these two sister planets of our solar system.

In this context, this study devoted to the development and performance assessment of synergistic retrieval algorithms for near-surface concentrations of CH_4 and CO from SWIR and IR passive remote sensing measurements for Earth and Mars atmospheres was organised into 4 Technical Tasks (Figure 1).

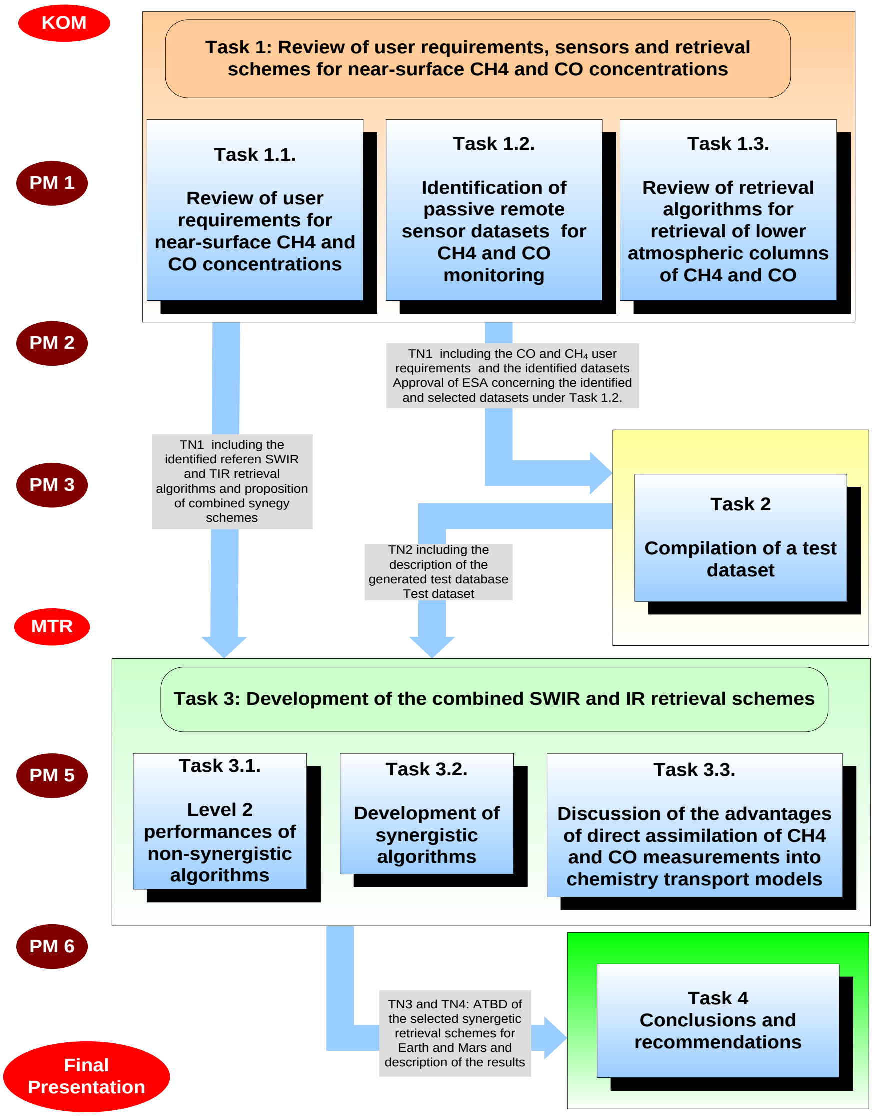

Figure 1 Study logic of SIROCCO

The following is a high level summary of the **conclusions** and **recommendations** resulting from the huge but very rewarding efforts deployed by the members of the consortium led by **NOVELTIS** and involving four other European institutes: **IASB-BIRA** and **ULB** from Belgium, **SRON** from the Netherlands and **IAPS** from Italy. It is impossible in practice to cover here all the cases of non-synergistic and synergistic retrievals of **CO** and **CH_4** which have been examined both on real and simulated satellite observations of **Earth** and **Mars**. The corresponding details are presented in the very complete **Final Report** of the **SIROCCO** project. In this report Table 4-9 (non-synergistic) and Table 4-19 (synergistic) are providing a synthesis of the retrievals for Earth, and Table 5-6 (non-synergistic) and Table 5-10 or 5-11 (synergistic) are gathering the corresponding retrievals for Mars. Spectral, geometrical and instrumental synergies have been considered whenever possible or fruitful. An added value of the project was a cross-fertilisation of methods and algorithms by scientists initially involved (separately) in Earth Observation and Planetary Science. They found a common and gratifying interest in sharing their experiences and results thanks to the SIROCCO project, an endeavour which would not have been possible without the ESA support.

2. General conclusions of the SIROCCO project

2.1. SIROCCO results versus user requirements

2.1.1. Earth

2.1.1.1. CO

The user requirements for CO measurement are 12% (Goal) and 18% (Threshold) of total uncertainty in the PBL for the three different applications described in Table 2-1 of TN1 in [RD3]). The Goal requirement is regarded as very stringent in view of the CO variability in the PBL at various spatial and temporal scales (e.g. a variation by a factor up to 5 for the seasonal cycle at Windhoek or Hyderabad). With the exception of MOPITT, which is not a spectrometer but is a gas correlation radiometer and thus was not considered in SIROCCO for L1/L1 retrievals, the operational sounder IASI is currently the only instrument able to provide CO information in the PBL. The ULB theoretical characterisation (with Atmosphit and FORLI) has shown that the CO retrieval error from IASI spectra in the PBL was never lower than 30% even in favourable situations of high positive thermal contrast. This result has to be mitigated, however, by the fact that it is strongly dependent on the assumed *a priori* variability. In conclusion, **the 12% requirement on the measurement of CO in the planetary boundary layer is hard to meet with IASI alone**. However, in cases of high positive thermal contrast (measurements during IASI morning overpass) **the 12% value is approached, for both highly negative and highly positive thermal contrast**. The MOZAIC-IASI comparisons at the five airports show too few situations of high negative thermal contrasts to draw conclusions, although it can be expected from the theoretical analysis that these would be the most favourable situations to probe CO at near-surface level.

In the S5 (SWIR only) simulated retrievals of SRON, the precision on the CO total column is between 2% and 5% depending on the cloud fraction. In the IASI-NG (TIR only) simulated retrievals by the same group, as in the IASI (TIR only) real retrievals of ULB, there is no sensitivity to CO in the PBL when the thermal contrast is near zero (below 2 K in absolute value). However, by combining IASI-NG (TIR) and S5 (SWIR) simulated spectra with the expected noise and spectral resolution and in quite realistic geophysical conditions over the west coast of the USA, SRON has shown (using the SICOR algorithm) that a meaningful CO sub-column (in the 0-2 km layer) can be retrieved for footprints over land with positive thermal contrast in the range 2-5 K (favourable to TIR) and the total column is well constrained by the SWIR information. Over the ocean (where the SWIR is not operative except possibly in the glint mode), the total column (with a contribution from the *a priori* in the PBL) is constrained by the TIR.

2.1.1.2. CH_4

From next generation satellite sounders, it is expected that the accuracy of the retrieved CH_4 total column will be better than 1%. In the SWIR this is already achieved (from GOSAT spectra) and was confirmed again in the SIROCCO project by SRON and IASB-BIRA. The threshold and goal user requirements as defined in TN1 [RD3] are 1% and 0.5% respectively for the CH_4 total column. Since the sensitivity to methane in the lower layers drops significantly in the TIR region, total column values need to rely on *a priori* information. The accuracy of the CH_4 total column from models is estimated to be around 2-3%. Therefore, total columns from TIR should be significantly better than the model error, but **biases largely exceeding the 1% threshold are observed** for TIR only retrievals. **Additional efforts are then needed to improve the accuracy of the TIR alone retrievals** and to meet the user requirements. Apart from the observed bias observed in all TIR retrievals of CH_4 (by SRON, IASB-BIRA and ULB), the scatter in the difference (**after bias correction**) between retrieved **TIR CH_4 total columns and TCCON is less than 1.5%**. The expected quality on profile information, however, is more demanding. A typical accuracy of 2% on a partial column of a 3 km layer above the surface is required. The DOFS in both the SWIR and TIR spectral regions are close to one and therefore no profile information can be retrieved from these spectra separately. For the SWIR spectral range the DOFS corresponds to the sensitivity of the total column, whereas in the TIR the sensitivity peaks in the mid to upper troposphere and DOFS of 1 may therefore be identified as a partial methane column in this altitude range. As shown by SRON retrievals, the partial column above 5 km can be retrieved from TIR spectra with 70% of the retrieved methane column originating from this altitude range and the remaining 30% coming from the methane abundance below 5 km captured by the vertical smoothing of the true profile with the help of the *a priori* profile. The averaging kernels describing the degree of vertical smoothing are consistent between the three teams of the consortium. An *ad hoc* procedure (scaling line intensities in the ν_4 band of CH_4) has been proposed by SRON to make **SWIR and TIR (hence synergistic) retrievals consistent** enhancing the DOFS to more than 1 + 1, i.e. getting useful sub-column information. But **further work is clearly needed to identify the causes of inconsistencies**, either in the forward model (including spectroscopic parameters) or on the retrieval strategy.

2.1.2. Mars

In TN1, the user requirements were originating from the recommendations of the Joint Investigation Definition Team (JIDT) in the paper by Zurek et al. (2009). Three applications were considered:

1. Hemispheric asymmetry of CO;
2. Seasonal variation of CO;
3. Detection of methane.

From the various tasks performed during the SIROCCO activity including the findings from non-synergistic and synergistic retrievals, new insights were highlighted enabling the consortium to update Table 2-2 of TN1.

3.1.2.1 CO

The investigation done during the PFS-CRISM comparison confirms that the user requirements for applications 1 and 2 given in Table 2-2 of TN1 can be met, but highlights the fact that a global coverage is necessary and in particular a global coverage with the suggested revisit time. This is essential to assess the geographical and temporal variability, such as hemispheric asymmetry and seasonal variations.

One value must be revised in this requirement table. The threshold value of the total column uncertainty was initially set to 40%, which corresponds to the CRISM's uncertainty. It was shown during the SIROCCO activity that this was not enough to characterize the two applications of interest (at least the uncertainty of the available data was too large at low latitudes). It was not possible to check if it was sufficient at high latitudes where the effects are expected to be stronger, since the coverage of CRISM is not sufficient at the poles for some critical values of the L_s changes. To keep future requirements global, it is suggested to **lower the threshold value to 22%** which is the uncertainty for PFS retrievals in the SWIR region and the goal to 10% which has not yet been achieved (the PFS TIR uncertainty is 13%). The extensive retrievals performed by IASB-BIRA using ASIMUT from simulated NOMAD and ACS spectra in the TIR (4.8 µm band of CO), in the SWIR (2.3 µm band of CO) and in several types of spectral and geometric synergies demonstrate that this uncertainty values are consistent with the expected performances of the two instruments to be orbiting Mars in the near future.

The vertical distribution of CO is also of interest and it would be possible to determine its vertical profile using solar occultation as shown by systematic studies of IASB-BIRA from simulated NOMAD and ACS spectra in low and high CO abundance cases. ULB has also shown that near-surface CO could be retrieved in the TIR band in favourable thermal contrast conditions. The threshold for the vertical resolution was defined as a few km and this value was used in Task 3 for simulated retrievals for the ACS and NOMAD instruments.

The arguments for the unchanged values of the table are not repeated here and can be found in the TN1 [RD3].

3.1.2.2 CH_4

Retrieving CH_4 from the SWIR spectra of PFS enabled the consortium to constrain the values suggested in TN1. Namely, to allow a PFS detection of CH_4 abundances as low as 5-10 ppbv, the averaging of 200 spectra recorded within a timeframe of less than 10 days is necessary. Statistical uncertainties of the retrieved average mixing ratios were lower than 7 ppbv with **3 cases of probable detection**. Revisit times could be defined as 1 measurement per hour as a threshold, to reach 200 measurements within 10 days and 1 measurement per half hour could be set as a goal. This is based on the results obtained with an instrument having a spectral resolution similar to that of PFS. With a higher resolution, one may not need to reduce this value drastically. The results obtained in solar occultation and in nadir with **NOMAD and ACS simulated spectra** seem to indicate that **retrieving abundances as low as 10 ppbv will require averaging or another retrieval strategy** that has to be designed. This means that a **10 ppbv retrieval is very challenging** and requires a specific parameterization of the retrieval procedure, in order to avoid negative values and oscillations at low altitudes. Considering the spread of the regions selected by IAPS for PFS retrievals and a Martian radius of 3390 km, calculations of the surface area on the geoid lead to values around 5 10^6 km^2. This could be considered as a threshold value, as this values is corresponding to CH_4 retrievals from real PFS spectra. A goal value could be lower than this value to get a better characterization of sources if they are at the surface. **A goal value of 10^6 km^2** is suggested, which correspond to a box of 20° both in latitude and in longitude. But much higher spatial resolution would be needed to detect and locate real point sources of CH_4 on Mars if they exist.

2.2. Added value and feasibility of the different synergistic approaches used in SIROCCO

2.2.1. Earth

2.2.1.1. CO

The spectral synergy for CO was not tested since real simultaneously recorded spectra around 4.8 µm and 2.3 µm are not available yet. However, this **synergy** has been analysed in simulations by SRON for **IASI-NG (TIR) and UVNS (SWIR) with interesting potential capabilities** for separating the PBL and mid-tropospheric sub-columns of carbon monoxide. But these results shall be consolidated and validated based on real measurements: such a spectral synergy (although from platforms that will have different equatorial crossing times) will be possible soon with IASI (TIR) and S5-P (SWIR) when this latter instrument is in the A-train orbit. The SIROCCO study has contributed to develop the corresponding retrieval tools and to prepare the combined exploitation of these measurements.

The geometric synergy between limb and nadir measurements has not been demonstrated to be especially powerful for **near-surface CO retrievals which are presently mature with IASI alone** in the nadir viewing geometry (when the thermal contrast is sufficient). The ACE-FTS L2 profiles (above 6 km which is usually the lowest tangent height for the solar occultation instruments) combined with the L1 spectra of IASI in the nadir viewing geometry do not enhance the precision of CO in the boundary layer as currently reached by this latter operational sounder on MetOp (i.e. precision of 30 % in the PBL and better in case of high positive or negative thermal contrast). This is explaining why the L1(TIR, nadir)/L1(TIR, solar occultation) geometric synergy has not been explored further in the SIROCCO study.

Performing this type of geometric synergy study for methane was not considered worth the effort, but such a task is recommended in the future to understand better the possible spectroscopic issues still remaining in the line shape modelling of CH_4 in the 7.8 µm band (see next paragraph).

2.2.1.2. CH_4

The usefulness of the spectral synergy between TIR and SWIR based on real GOSAT retrievals is presently hindered because of the biases in TIR only retrievals observed with the three different algorithms of SRON, IASB-BIRA and ULB. To circumvent this problem an *ad hoc* (but not fully justified) spectroscopic adjustment proposed by SRON allows retrieving **meaningful separate sub-columns** in the 0-5 km and 5 km-TOA altitude ranges using the **TIR/SWIR synergy**. The **consistency with TCCON** measurements is then satisfactory, with small but systematic residual biases still remaining. At present, GOSAT is the only sounder allowing to test the spectral synergy in perfect conditions since the IFOVs for the B4 (TIR around 7.8 µm) and B3 (SWIR around 1.66 µm) bands are in spatial and temporal coincidence (exact co-registration of different spectral information). This is why **solving the question of the consistency of the TIR retrievals is of high priority**. Updated **spectroscopic line parameters** and **line shape models for CH_4** should be carefully checked and tested since they could be causing the difficulties observed by the 3 groups of the SIROCCO consortium that performed methane retrievals in the TIR region. Other potential interfering species should also been tested to estimate their possible contribution to the absorption in this spectral region. The **geometric synergy** L1(IASI)/L1(ACE-FTS), not implemented in SIROCCO because of these difficulties, could in contrast be used to identify which aspect of the spectroscopy of CH_4 (or other interfering species) is currently impacting TIR (hence synergistic TIR/SWIR) retrievals. But in any case the **L1(TIR)/L1(SWIR) synergy for CH_4 has a great potential** for generating a consistent product (sub-columns or full profile with appropriate averaging kernels) that will avoid assimilating separately independent L2(TIR) and L2(SWIR) products which may not be physically consistent because of issues related to each spectral regions (lack of sensitivity in the PBL when the thermal contrast is small for TIR; lack of height resolved information and contribution of aerosols in SWIR). As recommended by preliminary analyses from SRON with a global/regional chemical transport model and assimilation system, it would be better to solve these problems at the L1 level rather than tuning the separate L2 products in the assimilation process.

2.2.2. Mars

The potential spectral synergy has been tested in the nadir viewing geometry for real PFS TIR and SWIR spectra since the corresponding L2 retrievals lead to consistent average CO mixing ratios. But this is **more a L2(TIR)/L2(SWIR) comparison rather than a L1(TIR)/L1(SWIR) synergy**. In the same PFS context the combination of temperature retrievals using CO_2 (in the TIR) and CO retrievals in the SWIR is also an example of L2/L1 synergy. Artefacts in the SWIR part of the spectrum covered by PFS are hindering the full use of existing spectra for the TIT/SWIR synergy. This spectral synergy for CO has been extensively tested on simulated spectra for NOMAD and ACS. **The SIROCCO study has been an efficient way to** promote this technique and to **prepare the operational algorithms for the EM/TGO mission**. Several synergies have been tested and the ASIMUT versatility is allowing for several inversion configurations. **The spectral synergies work well for NOMAD and ACS simulated spectra** in the L1/L1 and L2/L1 configurations in occultation as well as in the nadir viewing modes. In some cases the choice of the "profile" or "column" mode must be made depending on the information content of the spectra which is much less for CH_4 (with a very small mixing ratio) than for CO (a much more abundant species for Mars). The current noise level in the PFS LW band (i.e. the region covering the ν_4 band of methane around 7.8 µm) is too high for a detection in this spectral region, which explains that CH_4 has been searched in the ν_3 band of CH_4 around 3.3 µm in the so-called PFS SW or MIR region. A better signal to noise ratio of ACS spectra (if possible) could open the path for more systematic attempts to combine different bands in spectral synergy for the confirmation of methane detection in the Martian atmosphere.

2.3. Cross-fertilisation in SIROCCO

In addition to the team combined effort between Earth Observation and Planetology scientists which lead to fruitful exchanges of information, three types of Earth-Mars cross-fertilisation have been achieved by the SIROCCO project:

- within the corresponding IASB-BIRA teams, the ASIMUT code, originally designed for Earth atmosphere retrievals and then further modified and appliedfor use in the Mars atmosphere context, has been used for actual GOSAT CH_4 retrievals in the Earth atmosphere;
- between the IAPS and ULB teams, expertise on PFS spectra on one side and on nadir profile retrievals on the other side have been combined to demonstrate the possibility of profile retrievals of Martian CO whereas only column retrievals had been attempted previously.
- different RTMs originating from the Earth observation community and from the planetology community have been compared.

3. Recommendations

3.1. Summary and recommendations for synergistic retrievals CH_4 and CO for current and future missions (Earth)

With the new generation of atmospheric sounders IASI-NG(TIR) and S5 (UVNS) on MetOp-SG (in the 2020 time frame), CO and CH_4 retrievals will be performed operationally in separate TIR and SWIR spectral regions but should also be tested in **synergistic retrievals once the separate L2 products are validated and compared**. The joint assimilation of the L2 products (with the proper averaging kernels) within the state-of-the-art CTMs will be an additional tool to check their consistency. The TIR/SWIR **spectral synergy** (demonstrated within SIROCCO) will clearly contribute to provide a **better combined product for the complete vertical profiles of CO** (as demonstrated using simulated spectra) with a good separation of the PBL and the free atmosphere. The **efficiency of TIR/SWIR synergistic retrievals** of real **GOSAT** spectra **has also been demonstrated for CH_4** (with an increased accuracy of the complete mixing ratio profile). The question of co-registration will not be the limiting factor for the sounders of MetOp-SG since they will be accommodated on the same platform. Synergistic L1/L1 retrievals can be tested earlier (confirming the usefulness of the technique) when S5-P (free-flyer in the A-TRAIN constellation, to be launched in 2016) is in orbit by joint CO retrievals of spectra in the SWIR region (2.3 µm) with spectra of IASI in the TIR region (4.8 µm). **This synergy has been tested successfully within SIROCCO using the SICOR algorithm for simulated spectra for IASI-NG and S5,** and should be implemented in the S5-P ground segment using RemoTeC, which can be configured to process simultaneously several spectral windows for GOSAT (again as demonstrated within SIROCCO). But for CH_4, even if different SWIR windows can be used, **progress in the methane spectroscopy is needed in the TIR band around 7.8 µm**. This should be supported by further work on consolidated CH_4 TIR retrievals from real IASI spectra, as well as by additional TIR and synergistic SWIR/TIR retrievals of CH_4 from TANSO-FTS spectral still being accumulated by GOSAT.

3.2. Summary and recommendations for synergistic retrievals CH_4 and CO for current and future missions (Mars)

The tools developed within the SIROCCO project have been tested on both real PFS spectra and on simulated spectra for the future sounders on the ExoMars orbiter platform. The **potential for CO profile retrievals using PFS TIR spectra** (hence near-surface concentrations) has been demonstrated and should be implemented in further studies. The possible detection and quantification of CH_4 should be pursued and possibly published once confirmed by the IAPS team. The SIROCCO project has allowed IASB-BIRA to test extensively (with simulated spectra) various configurations of the **ASIMUT code for synergistic spectral or geometrical retrievals of CO** (and possibly CH_4 if its concentration is in the 10 ppbv range). The retrieval code should still be tailored to the actual detailed specifications and pre-flight characterisation of the **NOMAD** and **ACS** instruments, which still need to be performed. But the retrieval code has been extensively tested and will need optimisation for being fully operational. The SIROCCO project has contributed to this effort.