POTENTIAL OF CO2 RETRIEVAL FROM IASI

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Abstract

In the frame of a Research and Technology (R&T) study for the French Space Agency (CNES), NOVELTIS investigates the CO_2 retrieval accuracy for observations from space with different instrument types. The results obtained from the Infrared Atmospheric Sounding Interferometer (IASI) are presented here. The potential of CO_2 retrieval from IASI data is assessed, through the qualitative and quantitative analysis of two questions: expected accuracy of the CO_2 atmospheric concentration from the IASI infrared high resolution spectrum; impact of a specific cloud decontamination processing on the usefulness of the IASI CO_2 product. First results on the CO_2 retrieval accuracy and optimal CO_2 product design from the IASI spectrum are presented here.

A signal processing is developed to efficiently exploit the CO_2 information of the IASI spectrum, through Discrete Fourier Transform (DFT) filtering. Information content analyses and inversion experiments on simulated and real data are performed to assess the expected precision of retrieved CO_2 concentration, by taking into account the impact of the temperature, water vapour and ozone profiles uncertainties.

This analysis shows that one can retrieve the mean atmospheric CO_2 concentration from a single IASI spectrum with a precision better than 1%, and demonstrate the possibility to derive CO_2 profile information (2 pieces of information). The powerful signal filtering properties of the DFT data processing appears decisive, as it allows to stabilize and make more robust CO_2 retrieval of the total content and profile information.

A CO_2 information content analysis and CO_2 retrieval simulations are done using the Optimal Estimation Method. That work demonstrates the capability of IASI to retrieve the CO_2 from a single IASI measurement with a precision of about 1 % and a vertical profile of CO_2 on 2 atmospheric layers with a precision of 10-20 %.

It is also shown that the DFT method is decisive for a robust retrieval.

CO2 measurement requirements

Our current observing system of the global carbon cycle has a significant gap, as knowledge of the carbon cycle is based on sparse sampling on land, at sea and in the atmosphere. As a consequence, we cannot yet measure the components of the global carbon cycle with sufficient accuracy to balance the carbon budget. Improvements in the knowledge of the atmospheric CO_2 content, as well as in our understanding of the exchange mechanisms with sea and land surfaces, are therefore urgently needed for reliable predictions of the long-term anthropogenic increase of atmospheric CO_2.

To address this issue, greater geographical and seasonal coverage of CO_2 measurements in the atmosphere is required. In order to identify sources or sinks of CO_2, Requirements of about 1 % of the mean CO_2 mixing ratio over regional scales is stated (Rayner et al., 2001). The Infrared Atmospheric Sounding Interferometer (IASI) is one of the suitable instruments for monitoring atmospheric CO_2 from space. This study quantitatively explores the potential for IASI to derive atmospheric CO_2 information.

IASI measurements

IASI is dedicated to operational meteorology by measuring temperature and water vapour profiles in the lower atmosphere, as well as total content of trace gases such as CO, N_2O, O_3, CH_4 and CO_2.

It will be on board the METOP satellite series in a sun-synchronous orbit and providing two measurements of a given Earth location per day. Individual IASI measurement is composed of 4 samples with a diameter of about 12 km and intervals of 25 km along and across track at nadir. The scan duration of eight seconds and the horizontal spacing of the full Earth views are identical to those of the AMSU-A instrument as shown in figure 1. The IASI spatial density is estimated at 1000 samples for a 10°x10° area.

IASI consists of a Fourier Transform Spectrometer based on a Michelson Interferometer, coupled to an integrated imaging system which allows characterisation of cloudiness inside the spectrometer field of view. The instrument measures the infrared spectrum emitted by the Earth and provides spectra of high radiometric quality at 0.5 cm^{-1} apodised resolution from 645 to 2760 cm^{-1} (see figure 2).

In this study, we considered IASI data obtained through a specific acquisition process, the external calibration mode. In this mode the scanning mirror is fixed (e.g., at the nadir position), allowing the measurement of consecutive spectra very close in space and time (216 ms between two measurements). This provides series of spectra measuring mainly the same surface and atmospheric conditions. Such data sets are useful to validate retrieval algorithms, verifying the processing stability and providing an empirical computation of the noise.

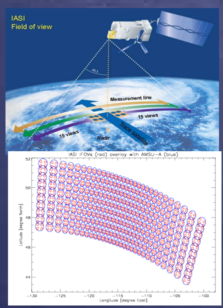

Figure 1: Spatial distribution of IASI and AMSU measurements

Data compression: DFT Method

The Discrete Fourier Transform (DFT) method is illustrated in figure 2. The atmospheric spectrum measured by IASI is simulated with the 4A radiative transfer algorithm. It exhibits a quasi-periodic line structure in specific CO_2 spectral windows. Selected windows of the spectrum are re-sampled on a periodic base built from the theoretic spectral transitions of the CO_2 lines. Finally, the DFT applied on these spectral windows provides the pseudo data that is composed of the mean signal, the fundamental and harmonics.

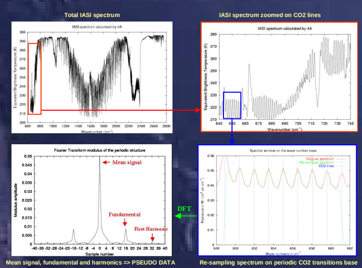

Figure 2: Description of the DFT method

Windows	DFT SNR	DFT SNR / √N	Spectrum SNR
W1	1074.8	150.5	138.0
W2	150.5	142.3	165.2
W3	138.0	206.7	206.0
W4	1357.7	282.7	216.9
W5	142.3	358.9	296.0
W6	165.2	323.4	333.0
W7	1825.5	312.3	304.6
W8	206.7	300.8	296.3
W9	1815.9	178.9	173.7
W10	2559.6	277.6	283.1
W11	831.3	88.6	71.2
W12	647.6	89.8	94.4
W13	57.8	5.3	3.3
W14	64.8	7.3	9.8
W15	1076.4	99.1	103.1
W16	689.9	84.9	89.6

Table 1: DFT Signal to Noise Ratio (SNR)

The pseudo data jacobians (data sensivity to CO_2) are obtained by calculating the DFT of the IASI spectrum jacobians and the pseudo data noise is obtained by the standard deviation of the DFT over 2000 noisy spectra.

The DFT was applied for 16 spectral windows that exhibit CO_2 absorption pattern (see table 1). The Fourier space analysis method allows information merging by increasing the SNR with a factor √N (number of window samples). The DFT processing is then equivalent to a data compression and allows to strongly reduce the computing time of calculations.

Data inversion: Optimal Estimation Method (OEM) formalism

Model direct:

- Radiative transfert model: $y = F(x) + \varepsilon$ (1)
- Linearisation around *a priori* x_B: $y - F(x_B) = H(x - x_B) + \varepsilon$ (2)

Inverse problem:

- Cost function minimisation: $\chi^2 = [y-F(x)]^T R^{-1} [y-F(x)] + [x-x_B)]^T B^{-1} [x-x_B]$ (3)
- Retrieval: $x_A = x_B + D\,[y-F(x_B)]$ (4)
  $x_A = [1-G]\,x_B + G\,x$ (5)

Error analysis:

- Retrieval error: (1)+(4) => $x_A - x = D\varepsilon + [G-I]\,(x-x_B)$ (6)
- Covariance matrix errors: $A = D R D^T + [G-I]\,B\,[G-I]^T$ (7)
  $A = A_m + A_s$ (8)

x : true state
x_B : *a priori* state (background)
x_A : retrieved state
y : measurement
F : observation model
ε : measurement error
$H = \delta F/\delta x$: jacobians
R : measurement error covariance matrix
B : *a priori* error covariance matrix
$D = [H^T R^{-1} H + B^{-1}]^{-1} H^T R^{-1}$: contribution functions
$G = DH$: averaging kernels (retrieval weighting functions)
I : identity matrix
A : retrieval error covariance matrix
A_m : error due to measurement (noise)
A_s : error due to *a priori* (smoothing error)

CO2 product definition

The determination of the IASI performance for CO_2 total content or profile retrieval has been done using the OEM formalism. The objective of the product definition is to design a CO_2 retrieval product able to optimise the information content provided by the IASI data, and to exploit the (low) troposphere information as far as reasonably possible.

Data-oriented product: In the retrieval process, product information content comes from the data and from the *a priori* CO_2 information. In an optimal approach, this *a priori* is fixed by our best knowledge of CO_2, and it controls the proportion of information coming from the measurement itself (only the information improving the prior knowledge is used). Figure 3 illustrates how the data information is modulated by variation of the CO_2 *a priori* error. In particular, the number of pieces of information changes from 1 to 4 and the sensitivity to troposphere levels is increased when the prior error increases from 5 % to 20 %. In this study we use a 20 % *a priori* error, which represents a good compromise between reasonable knowledge and full exploitation of the data signal

CO2 A priori error	5 %	20 %
DOFS	1.1	3.8

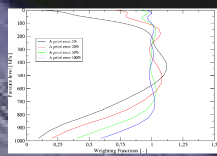

Figure 3: Degree Of Freedom For Signal and Weighting functions of CO_2 retrieval from IASI spectrum obtained with different levels *a priori* error

State vector : CO_2 (total content or profile) plus Surface Température		
Model parameters	Error used in this study	IASI level 2 error
Température profile	2 K	1 K
Humidity profile	30 %	10 %
Ozone profile	80 %	10-30 %

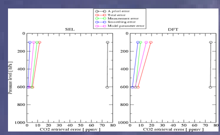

Figure 4: 2-level profile CO_2 retrieval errors : *a priori* (black), total error (red), measurement error (green), smoothing error (blue) and model error (magenta).

State vector and model error: Sensitivity studies indicates that Surface temperature as well as temperature, humidity and ozone profiles impact on the IASI CO_2 retrieval. From these studies, an optimal retrieval process has been designed : it considers the retrieval of CO_2 simultaneously with surface temperature, and the full variance/covariance error figures of temperature, humidity and ozone profiles provided as input information to the retrieval process. Figure 4 shows the retrieval error parts coming from data, *a priori* and model errors for a 2-levels CO_2 profile. Note that the total error should be reduced when IASI level 2 products will be used as inputs.

IASI CO_2 products: 3 CO_2 products are considered from IASI: total content, 2-levels and 3-levels profiles.

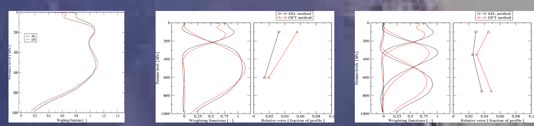

Figure 5: Weighting functions and relative errors of CO_2 products retrieved from IASI. When DFT data processing is usde (red) or not.

CO2 retrieval results

CO_2 total content and profiles are retrieved from series of real IASI spectra measured in external calibration mode. These retrieval experiments allow to validate the retrieval process robustness and to verify the theoretical error estimate.

CO_2 total column retrieval: Results of CO_2 total column amount (TCA) for 25 consecutive spectra are presented in Figure 6. The TCA is given in ppmv that represents the mean Volume Mixing Ratio (VMR) in the column. The results are very stable, and the variability is consistent with the theoretical error bars. The error is about 1.5%. Results are similar when using DFT processing (red) or not (black).

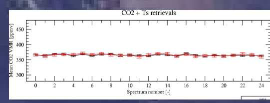

Figure 6: CO_2 total column retrieval (ppmv) for 25 consecutive IASI spectra, when DFT is used (red) or not (black).

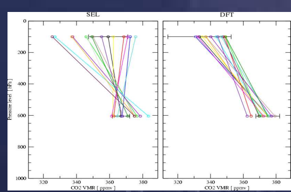

Figure 7: 2-level profile CO_2 retrieval (ppmv) obtained from 25 consecutive IASI spectra, when DFT is used (right panel) or not (left panel).

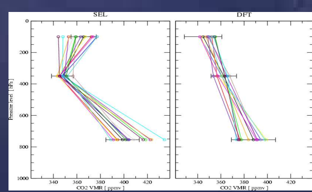

Figure 8: 3-level profile CO_2 retrieval (ppmv) obtained from 25 consecutive IASI spectra, when DFT is used (right panel) or not (left panel).

CO_2 profile retrieval: Results of CO_2 profile retrievals for 25 consecutive spectra are presented in Figure 7 (2-level profiles) and Figure 8 (3 level profiles).

Both retrievals experiments illustrate the role of the DFT data processing for the stability of the retrieval, clearly indicating that the filtering properties of this processing is decisive for exploiting profile information from IASI data

The error bars of the CO_2 profile elements are relatively large however: about 10 ppmv for tropospheric CO_2 and 20 ppmv for stratospheric CO_2 in case of 2-level profile retrieval. Note however that these errors depend on the accuracy of temperature, humidity and ozone information used as inputs. This information is no optimal in our experiments, and should be greatly improved by using IASI level 2 products

Conclusions

A signal processing is developed to efficiently exploit the CO_2 information of the IASI spectrum, through Discrete Fourier Transform (DFT) filtering. Information content analyses and inversion experiments on simulated and real data are performed to assess the expected precision of retrieved CO_2 concentration, by taking into account the impact of the temperature, water vapour and ozone profiles uncertainties.

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Perspectives

The validation on real IASI data has to be extend :

- on a significant number of IASI data in order to obtain an exhaustive validation of CO_2 retrievals on two and three levels
- with IASI data measured in coherence with independent measurements of CO_2.

Then, one can study how it could be possible to improve the CO_2 retrieval in terms of precision or capability to detect sources or sinks of CO_2. That could be done for example by :

- spatial and temporal averages of CO_2 retrievals
- adding independent sources of information in order to improve CO_2 retrieval in the lower troposphere
- improving the knowledge of model parameters by using for example IASI level2 products
- lower troposphere CO_2 retrieval by differential processing on heterogeneous scenes.