Derivation of tropospheric carbon dioxide and methane concentrations in the boreal zone from satellite-based hyper-spectral infrared sounders data

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Introduction

The development of space-borne hyper-spectral IR sounders (AIRS/EOS-Aqua, IASI/MetOp) opens new opportunities for detecting the variations of atmospheric carbon dioxide (CO2) and methane (CH4) concentrations. The capabilities to retrieve atmospheric column-average CO2 mixing ratio and similar column-average CH_4 mixing ratio (or CH4 columns) from satellite measurements is of significant importance in the context of global carbon cycle research, climate change studies and due to sparse network of ground-based CO2&CH4 observations. Bearing in mind these issues the main objectives of our research were as follows:

- Improvement of the technique for column-average CO2 mixing ratio (Q_{CO2}) retrieval in the upper troposphere from AIRS/EOS-Aqua data over Western Siberia;
- Validation of Q_{CO2} retrievals against aircraft flask CO2 observations (over boreal zone);
- Development and testing of the novel technique for tropospheric CH4 column (CA_{CH4}) retrieval from IASI and AIRS data.

This paper presents at first an updated status of Q_{CO2} retrieval scheme based on clear-sky or cloud-cleared AIRS inversion algorithm. The validation effort carried out with real AIRS data for two areas in the boreal zone of Western Siberia (Novosibirsk and Surgut regions) and for 10 months of year 2003 demonstrates the successful performance of proposed technique.

With respect to the CH4 column retrieval from AIRS and IASI data the approach has been developed based upon the application of iterative physical inversion algorithm to clear-sky AIRS or IASI data in the subsets of CH4 – dedicated super- channels (linear combinations of measurements in temperature- and CH4- dedicated channels). Using the data in super-channels reduces the effect of inaccurate temperature profile T(p) knowledge on accuracy of CA_{CH4} retrievals in sounding points. The performance of the retrieval algorithm is evaluated in the case study experiment involving datasets of IASI and AIRS data covering Kiruna (Sweden) region and complemented with quasi-synchronous and collocated ground based and radiosonde observations as well as with AIRS-based L2 retrievals.

Methodology of Q_{CO2} Retrieval from AIRS data

The sensitivity studies based on RTM SARTA simulations of clear-sky AIRS measurements (Strow et al., 2003) resulted in the selection of 2 subsets of CO2 dedicated channels (9 LW channels within the band 699-705 cm^{-1}; 6 SW channels within the band 1939-2107 cm^{-1}) with strong responses to CO2 variations and minimum sensitivity to main interfering factors, namely inaccurate knowledge of state vector components (including surface temperature and emissivity, atmospheric water vapor and ozone profiles, etc.).

Fig. 1, 2 demonstrate the CO2 Jacobians for LW and SW CO2-channels. The AIRS radiances in CO2-cnannels have maximum sensitivity to CO2 variations in the mid- to high-tropospheric layer and minimum sensitivity to variations of above interfering factors.

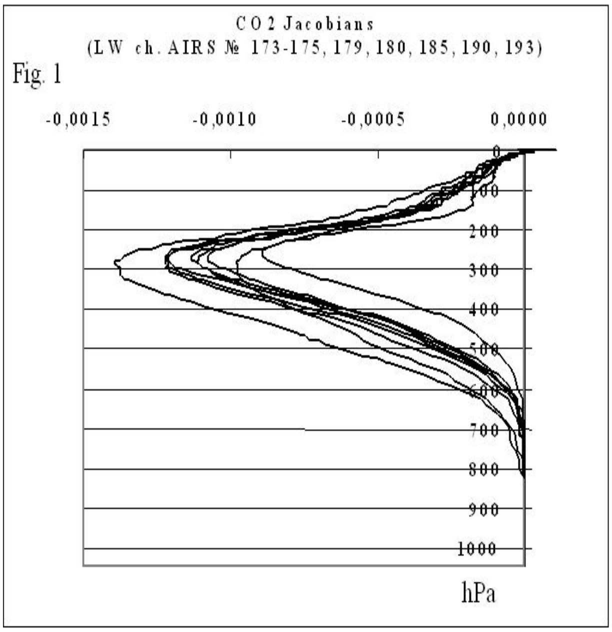


Fig. 1 CO2 Jacobians for LW CO2-channels

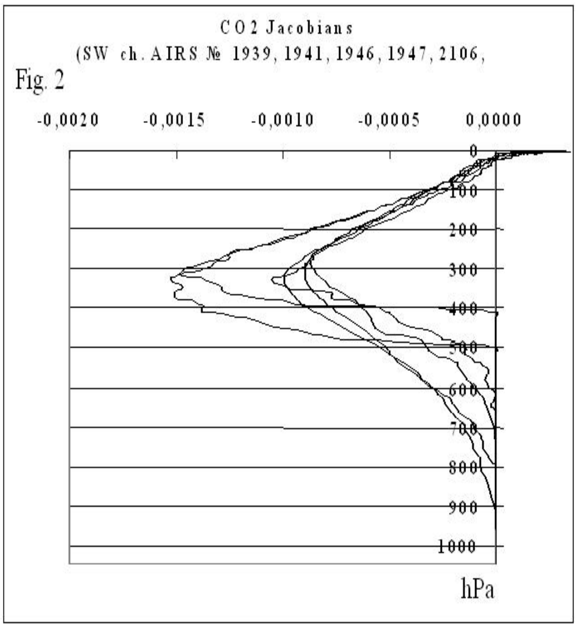


Fig. 1 CO2 Jacobians for SW CO2-channels

The improved technique for AIRS- based Q_{CO2} retrieval developed in (Uspensky et al., 2007) and similar to (Chahine et al., 2005) can be summarized as follows:

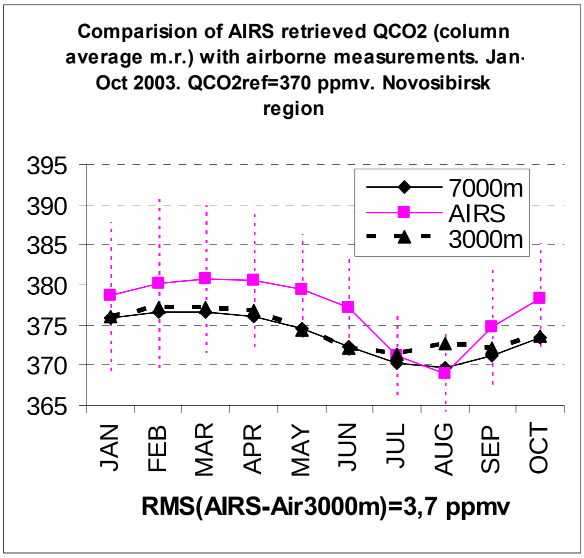
- Clear-sky and cloud-cleared radiances (brightness temperatures B_T^{obs}) measured in CO2-dedicated channels are used for Q_{CO2} retrieval;
- Forward calculations of synthetic brightness temperatures, B_T^{calc}, are performed using RTM SARTA with reference values Q^{ref}_{CO2} (Q^{ref}_{CO2} in the range 370-385 ppmv) and ancillary information (AMSU-based temperature profile T(p) retrievals and AIRS L2 retrievals of other state vector components);
- Monthly averaged biases$\langle B_T^{obs}$-$B_T^{calc}\rangle$are specified beforehand for the Region of Interest (ROI);
- Estimating Q_{CO2} is carried out using physical inversion algorithm, namely the Gauss-Newton iteration algorithm is applied separately to bias-corrected AIRS data in LW and SW CO2-channels in order to produce "independent" Q_{CO2}(LW) and Q_{CO2}(SW) retrievals;
- Spatial/temporal (median) filtering is performed for the clusters of {Q_{CO2}(LW)} and {Q_{CO2}(SW)} retrievals;
- The final monthly averaged estimate Q_{CO2} (AIRS) is produced as a linear combination of filtered Q_{CO2}(LW) and Q_{CO2}(SW) values (if they are consistent to each other).

The performance of described retrieval technique has been evaluated in the seria of validation exercises for three ROIs, involving samples of real AIRS data.

Validation exercises: CO2 retrievals over Siberian boreal zone and Kiruna region

The series of retrieval experiments has been conducted for a sample of more than 600 granules of actual AIRS data that were downloaded together with AIRS L2 retrievals and AMSU-based T(p) retrievals for pre-selected ROIs and time period between January and October 2003 (1-2 granules daily) from the site http://daac.gsfc.nasa.gov/data/dataset/AIRS/02_L2_Products/index.html. The Q_{CO2}(AIRS) retrievals are inter-compared with the results of air-borne measurements (Arshinov et al., 2005). The first region of air-borne surveys is located at the right bank of the southern part of the Ob Reservoir. The air-borne measurements of CO2 concentration at heights of 0.5- 7.0 km (available are the data at heights of 1, 3, and 7 km) cover the region 54° 08'-54° 33' N, 81° 51'-82° 40' E., moreover the boreal area consists 90% of coniferous trees. Similar observations have been conducted also for the second ROI, namely, Surgut region (60-62°N, 70-75°E); available are the data at 1 and 7 km. Other details regarding both ROIs (including images of both areas) can be found in (Uspensky et al., 2007). The monthly averaged air-borne CO2 observations have been compared to final Q_{CO2}(AIRS).

Figure 3 presents the comparison of AIRS retrieved Q_{CO2} with air-borne measurements for Novosibirsk and Surgut regions.



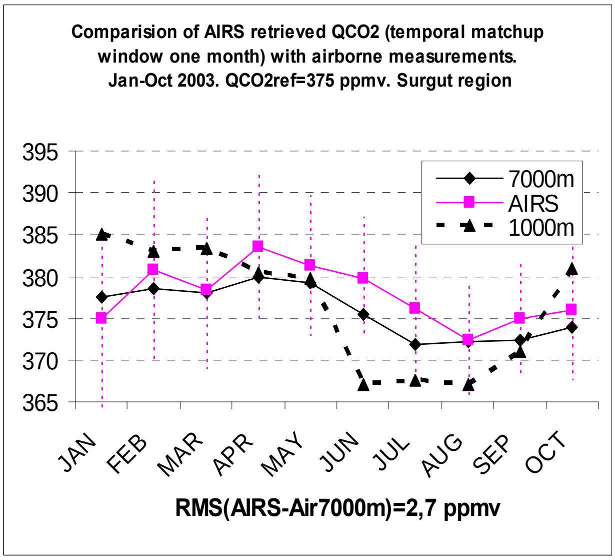


Fig.3a Q_{CO2} retrievals (Novosibirsk) Fig.3a Q_{CO2} retrievals (Surgut)

Besides, in order to specify the most appropriate temporal mutchup window for averaging, the Q_{CO2} retrieval experiment has been conducted for the same Surgut region with 2 weeks temporal mutchup window, see Fig. 4. As follows from Fig. 3b) and Fig. 4 comparison, it is possible to reduce sought temporal window from 4 to 2 weeks without significant loss of Q_{CO2} retrieval accuracy.

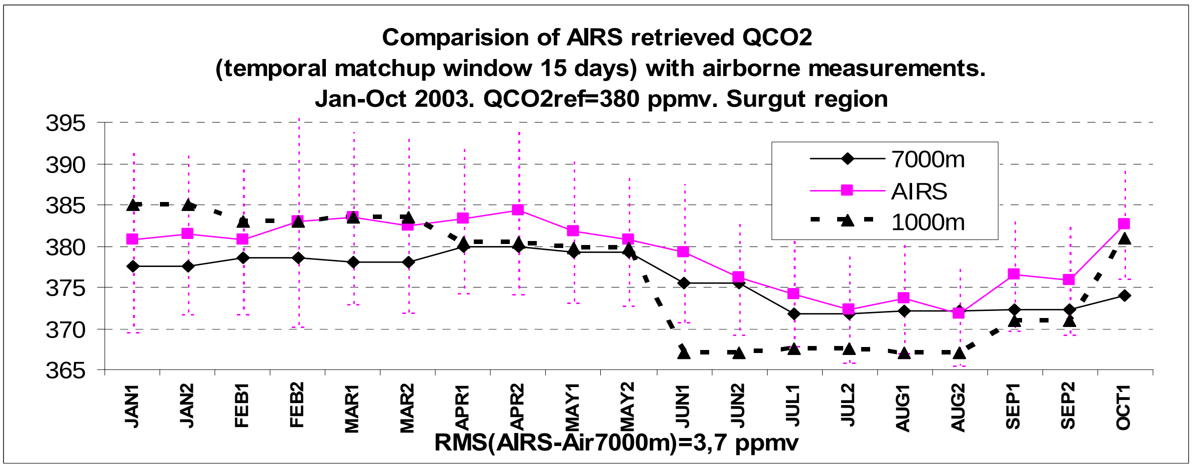


Fig. 4 Q_{CO2} retrievals (Surgut)

The results of validation exercise performance for both ROIs can be summarized as follows:

The inversion of actual AIRS data for 2 areas (Western Siberia) enables to retrieve Q_{CO2} values that agree reasonably with seasonal trend of those identified from *in-situ* air-borne measurements and have a precision of about 1% (comparing to air-borne measurements at 7 km). The temporal match-up window between 2 weeks and 1 month is suitable for Q_{CO2} retrievals averaging.

Along with described validation exercises the performance of above Q_{CO2} retrieval algorithm has been evaluated in a case study experiment involving AIRS data and respective AIRS L2 retrievals covering Esrange (Kiruna, Sweden) area. This dataset has been compiled as complementary to dataset including IASI/MetOp, IASI balloon-borne instrument measurements together with ground-based and

radiosonde observations. The last one was kindly provided by Dr Claude Camy-Peyret (Université Pierre et Marie Curie et CNRS Physics department, LPMAA, France), see (Payan et al., 2007).
The results of experimental AIRS based Q_{CO2} retrievals are presented in Table 1.

Table 1: Experimental retrieval of Q_{CO2} from AIRS data 21-23 Feb. 2007, Esrange/Kiruna

First guess, ppmv	SW channels			LW channels			SW+LW	
	Number of pixels	Std.d	QCO2	Number of pixels	Std.d	QCO2	Std.d	QCO2
375	184	10,7	387,5	227	9,8	393,4	7,2	390,7
380	206	12,0	389,3	229	9,6	393,6	7,5	391,9
385	222	13,3	390,5	228	9,6	393,8	7,8	392,7
390	225	13,8	391,1	226	9,5	394,0	7,8	393,1
395	219	13,6	391,4	224	9,3	394,0	7,7	393,2

The retrievals have been performed using various first guess for Q_{CO2} (1-st column of Table 1). It is seen that the Q_{CO2} estimate based on AIRS data in LW CO2-dedicated channels (columns 5-7) as well as "combined" Q_{CO2} estimate (columns 8, 9) are sufficiently robust with respect to first guess changes. In spite of absence collocated "ground truth" Q_{CO2} observations, the analysis of Table 1 enables to confirm the above conclusions regarding the performance of proposed Q_{CO2} retrieval technique. The feasibility of Q_{CO2} retrievals is also confirmed (indirectly) via comparison with IASI based Q_{CO2} retrievals from (Payan et al., 2007). This conclusion can be treated as preliminary, accounting for rather limited samples of AIRS and IASI data used.

IASI- and AIRS-based CH4 column retrievals: first results
Sensitivity studies carried out with synthetic clear-sky IASI measurements enabled to select subset of 4 CH4-dedicated channels within the methane absorption band around 7.7 µm, see Fig.5.
According Fig.5 the IASI measurements in 4 channels with wave to numbers 1332.5, 1341.75, 1346.75 and 1342.75 cm^{-1} being the most sensitive to CH4 variations have reduced sensitivity to variations of water vapor (H2O) and ozone (O3) concentrations treated as main interfering factors. It allows to select these channels as CH4-dedicated. The plots of CH4-Jacobians for these channels (Fig.6) show maximum sensitivity to the CH4 variations in the troposphere with a peak around 10 km. This fact is also confirmed by the behavior of averaging kernels, presented at Fig. 7.

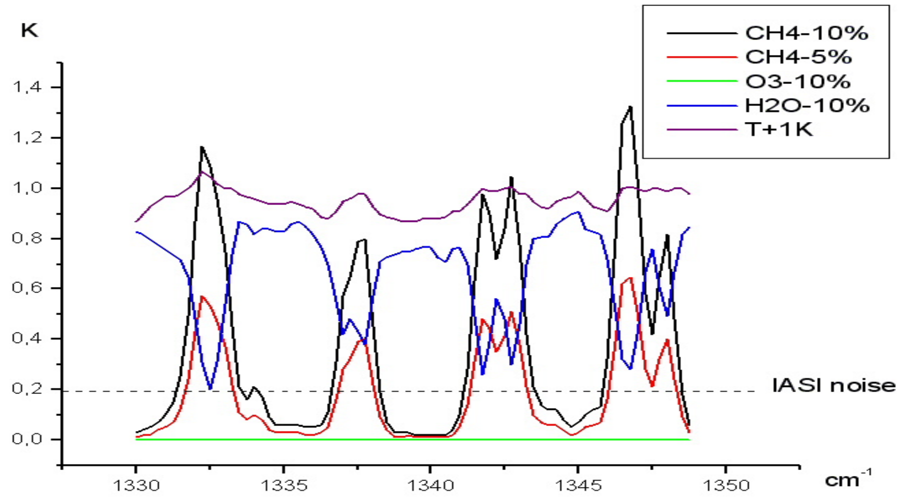
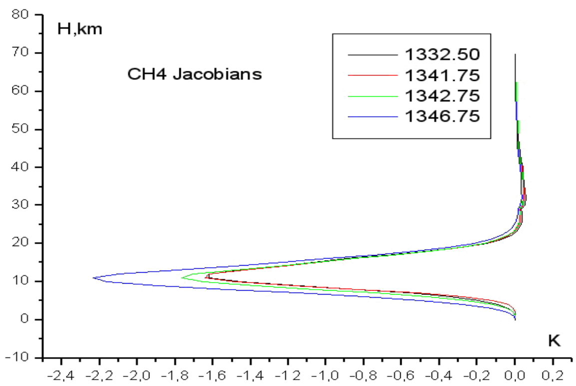


Fig.5: Brightness temperature sensitivity to changes in CH4, O3, H2O concentration and temperature variations.



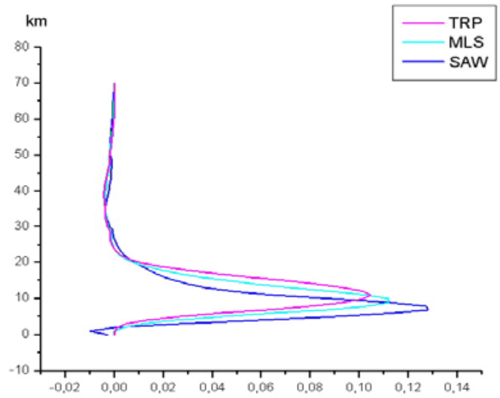


Fig. 6: CH4 Jacobians in selected IASI channels

Fig. 7: Averaging kernels for CH4 column retrievals (various atmospheric models)

The plots of averaging kernels obtained for CH4 column retrievals demonstrate strong sensitivity to the CH4 concentration in the layer between 7 and 15 km, see also (Turquety et al., 2004)
Besides, in order to reduce the effect of profile T(p) uncertainties on the accuracy of CA_{CH4} assessment four CH4-dedicated super-channels have been built. Fig.8 presents the temperature Jacobians in selected IASI CH4-channels and in “conjugated” channels from 15 μm band. The similarity of temperature jacobians for 4 channel pairs enables to form 4 super-channels with temperature Jacobians close to zero and thus to reduce the sensitivity of “signals” in these super-channels to temperature variations.
Thus it is reasonable to form the following set of super-channels, namely:
I: 1332.50-706.50; II: 1341.75-715.25; III: 1342.75-741.25; IV: 1346.75-714.0 cm^{-1}.
Use of superchannels provides valuable decrease in noise level, especially in noise induced by inaccurate knowledge of temperature at sounding points. It is illustrated by Fig. 9: the contribution of CH4 variations to signal exceeds significantly those induced by T and H2O-variations.
The CH4 retrieval approach is based on the physical inversion and utilizes clear-sky IASI data in listed super-channels and a priori specified T- and water vapor profiles. Similar inversion algorithm is applied to AIRS data.

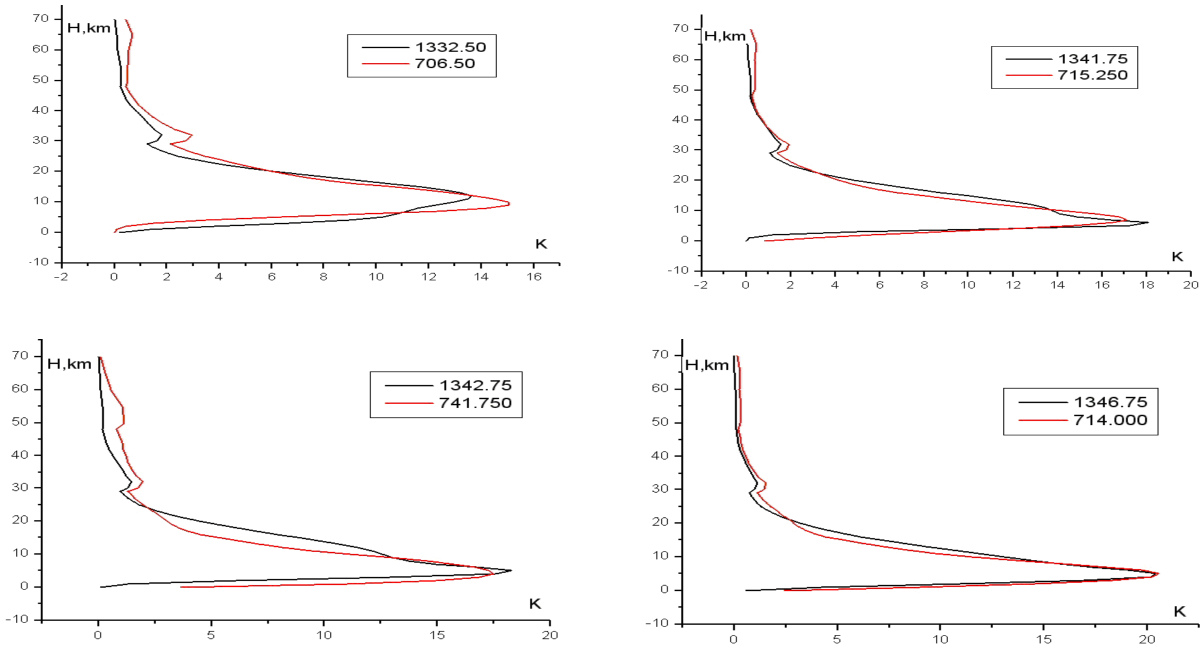


Fig.8: Temperature Jacobians in “conjugated” IASI channels(CH4 7.7 μm and CO2 15 μm absorption bands).

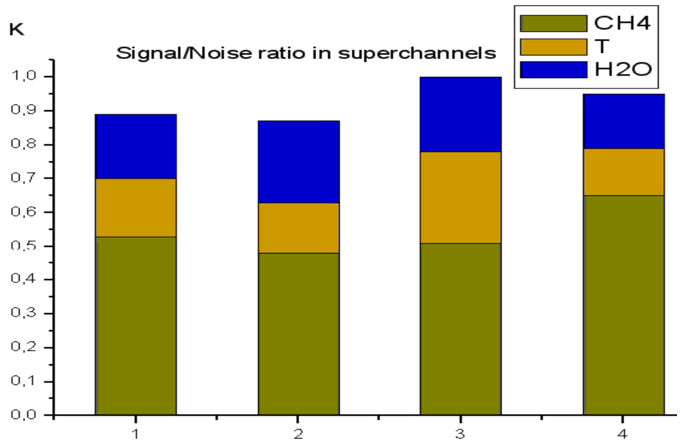
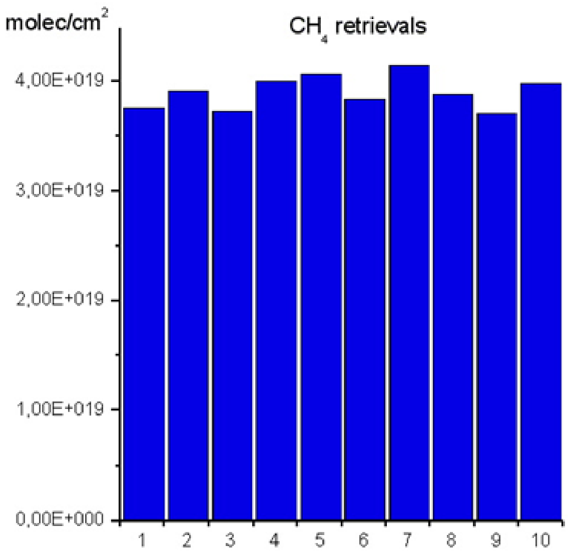


Fig.9: Signal/Noise ratio,K in superchannels (CH4-5%; H2O-10%, T+1K)

Case study experiment

The performance of above retrieval algorithm was evaluated in a case study experiment using the above described dataset for Esrange (Kiruna, Sweden) area.

The examples of IASI and AIRS-based CH4 column retrievals are presented at Fig.10 (left and right panels respectively).



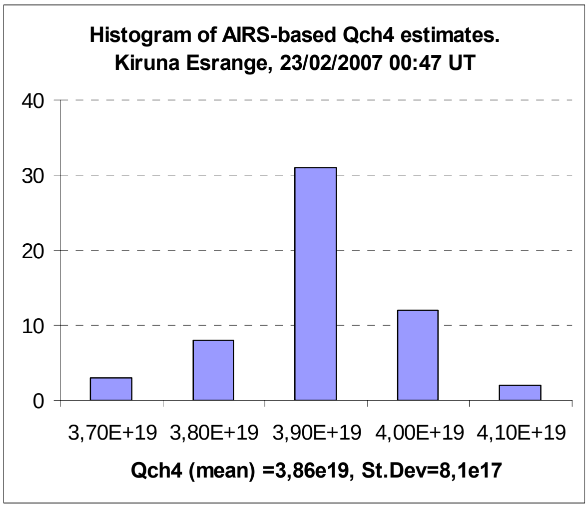


Fig.10: Distributions of IASI-based (10 sub-pixels) and AIRS-based (about 60 FORs) QCH4 retrievals

IASI data inversion. The collocated radiosonde observations (temperature and water vapor profiles) are used as ancillary information. The Gauss-Newton iteration algorithm was applied for the inversion of bias-corrected IASI data in four CH4-dedicated super-channels. The final residuals, i. e. differences between observed and calculated radiances are demonstrated at fig. 11 (not more than 3 iterations). AIRS data inversion. The AIRS L2 retrievals (temperature, water vapor and ozone profiles together with surface temperature and emissivity) were used as ancillary information. The Gauss-Newton iteration algorithm was applied to bias-corrected AIRS data in four CH4-dedicated channels. Comparison of both kinds of CA_{CH4} retrievals demonstrates their closeness and it confirms indirectly the efficiency of proposed IASI&AIRS data inversion technique.

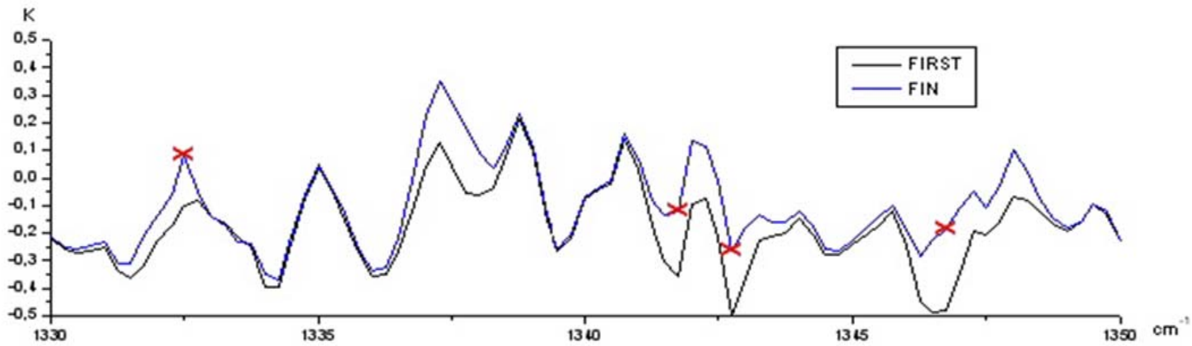


Fig.11: First guess and final residuals for IASI spectra, crosses mark the IASI channels used for CH4 retrieval.

Acknowledgments

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References

Arshinov M. Yu., B.D.Belan, G.Inoue et al., 2005: *Advances in the geological storage of carbone dioxide. Ed. S. Lombardi, I .K. Altunina, S.T. Beanbien*. Kluwer Acad. Publ., 11-16.

Chahine M., et al. 2005: *Geophys. Res. Lett.,* 32, L22803, doi: 10.1029/2005GL024165.

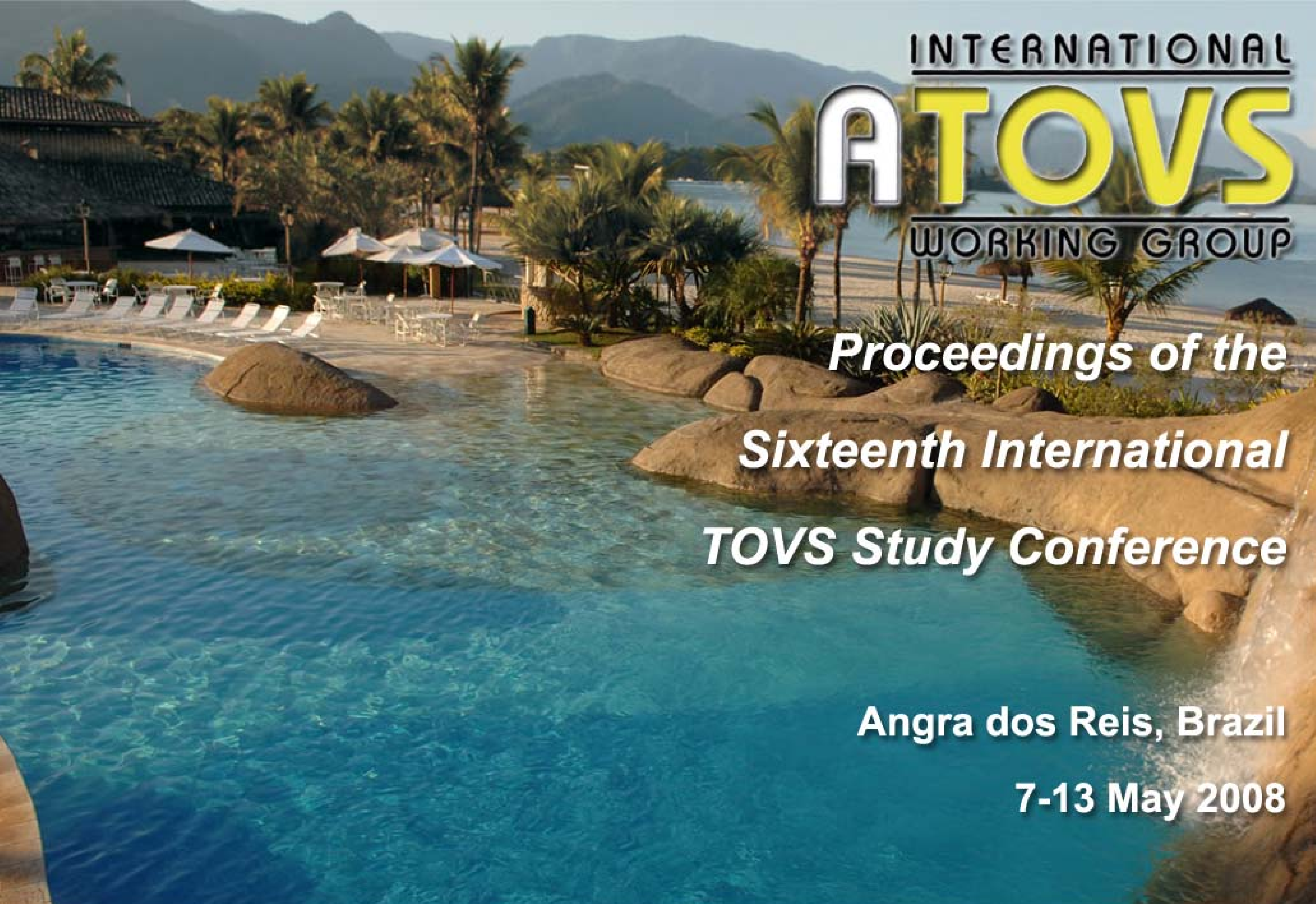
Crevoisier C., A. Chedin, N.A. Scott, 2003: *Q.J.R. Meteorol. Soc*. v. 129. 2719-2740.

Payan S.,C.Camy-Peyret, et al.,2007: *IASI Conf.,Anglet,France, 13-16 Nov.2007*

Strow L.L., et al., 2003: *IEEE Trans. Geosci. Rem. Sens*. v.41, N 2, 303-313.

Turquety S., et al., 2004: *J. Geophys. Res*., v.109, D21301, doi: 10.1029/2004 J D004821.

Uspensky A.B., et al. 2007: *Proc. "The joint 2007 EUMETSAT Meteor. Sat. Conf. and 15th AMS Sat. Meteor. & Oceanogr. Conf". Amsterdam, The Netherlands, 24-28 Sept. 2007*.



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