Retrieval of Atmospheric Trace Gases Variability with Satellite Advanced IR Sounders

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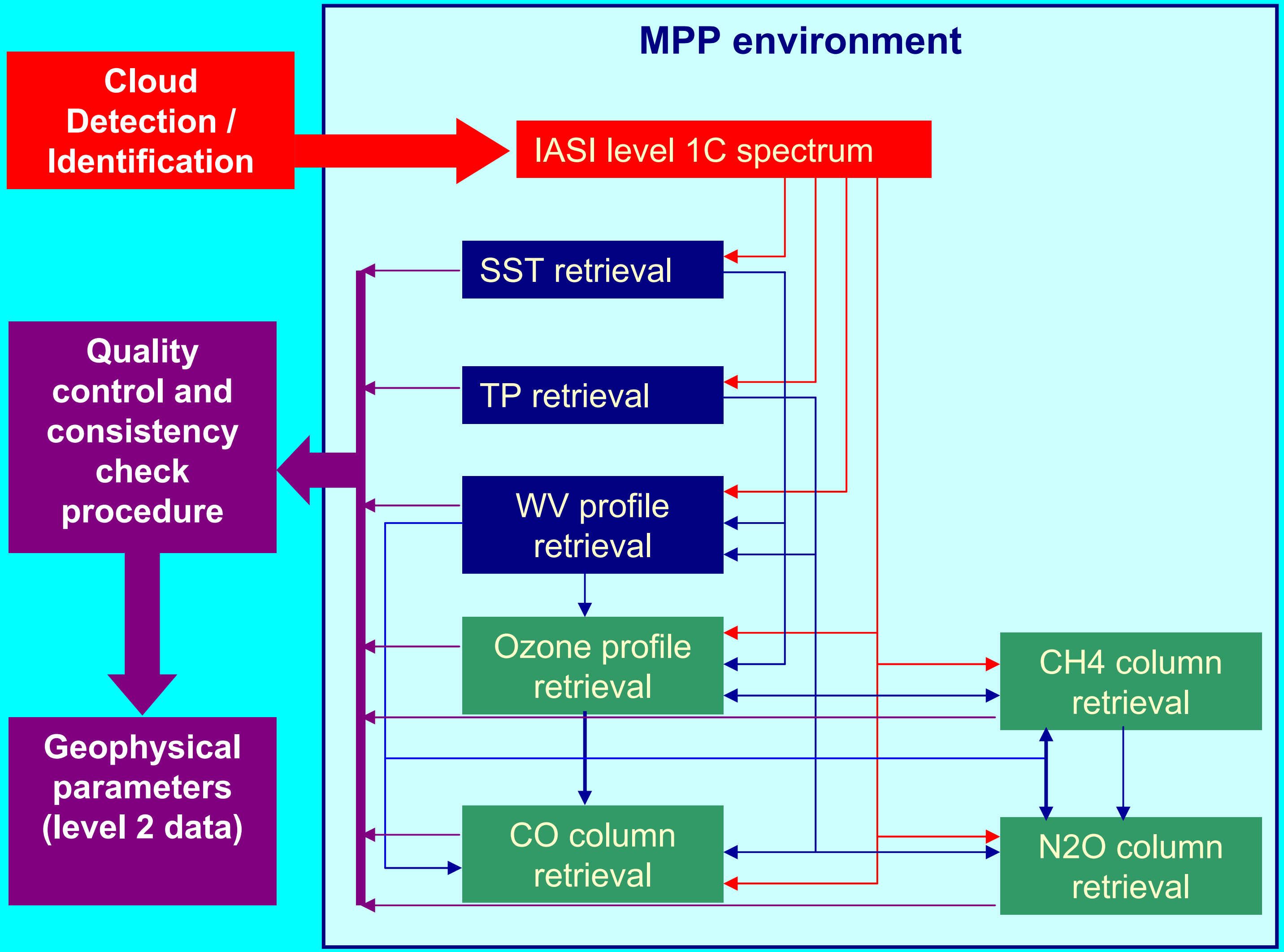
Outline

- **IASI-based retrieval of atmospheric CH4, N2O, and CO columns**
- **Detecting of CO2 variations from AIRS/Aqua data**
- **Concluding remarks**

IASI-based retrieval of atmospheric CH4, N2O, and CO columns

Methods overview

Methods overview : MPP Functional design

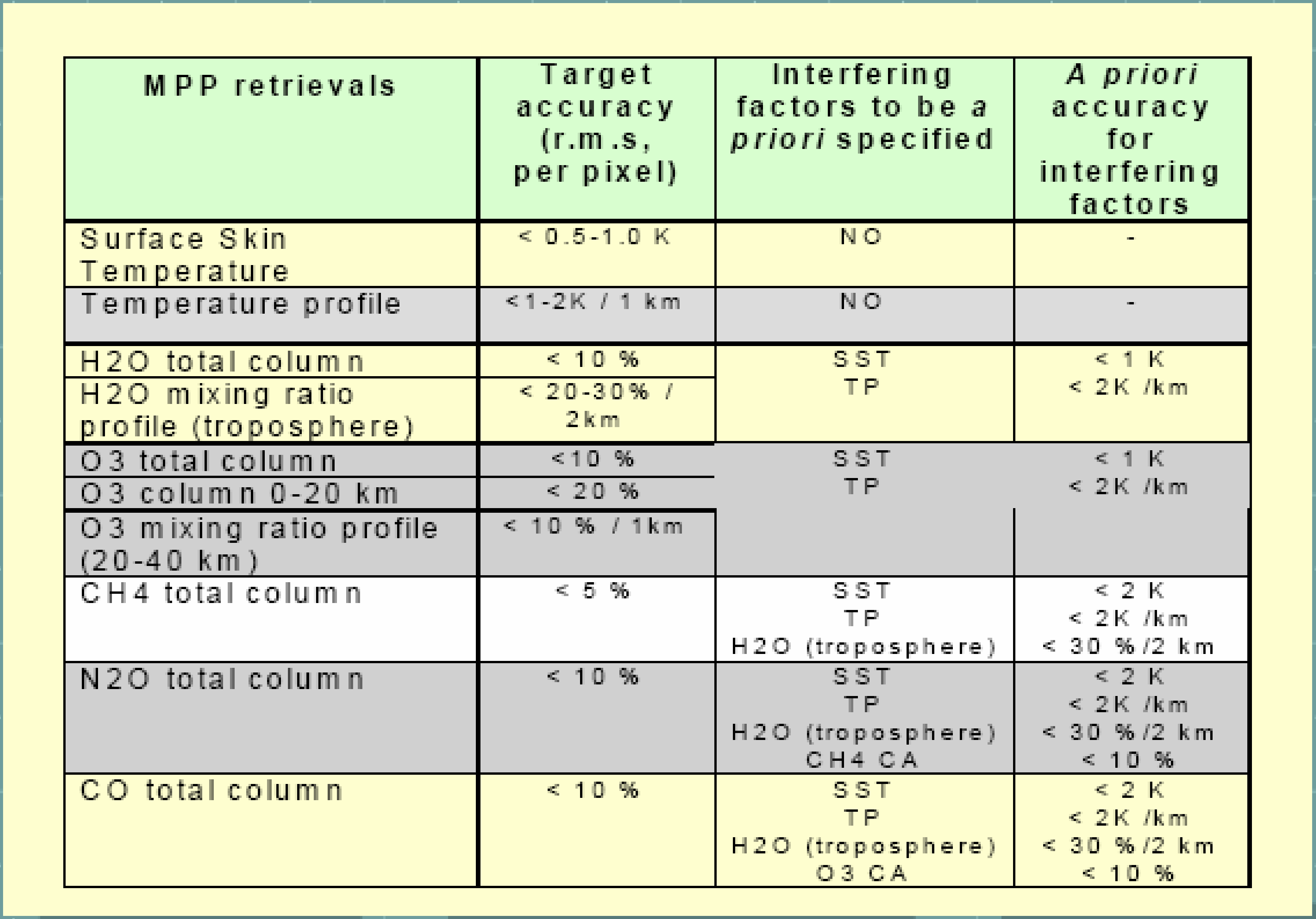


Methods overview : MPP Content design

The **Modular Prototype Processor (MPP)** is the integrated software application capable of a self-contained execution of the procedures to retrieve the geophysical parameters from IASI level 1c data. MPP at the moment provides the following retrievals :

	exploits
land or sea surface skin temperature (SST)	measurements only
temperature profile (0-40 km with 1 km resolution)	measurements only
H_2O total columnar amount	SST and TP retrievals
H_2O mix. ratio profile (0-10 km with 1 km resolution)	SST and TP retrievals
O_3 total columnar amount and partial column in between 0-20 km	SST and TP retrievals
O_3 mix. ratio profile (20-40 km with 1 km resolution)	SST and TP retrievals
Minor gases total columns: CH_4 N_2O CO	Retrievals for: SST, TP, H_2O SST, TP, H_2O, CH_4 SST, TP, H_2O, O_3

MPP overview: Target characteristics

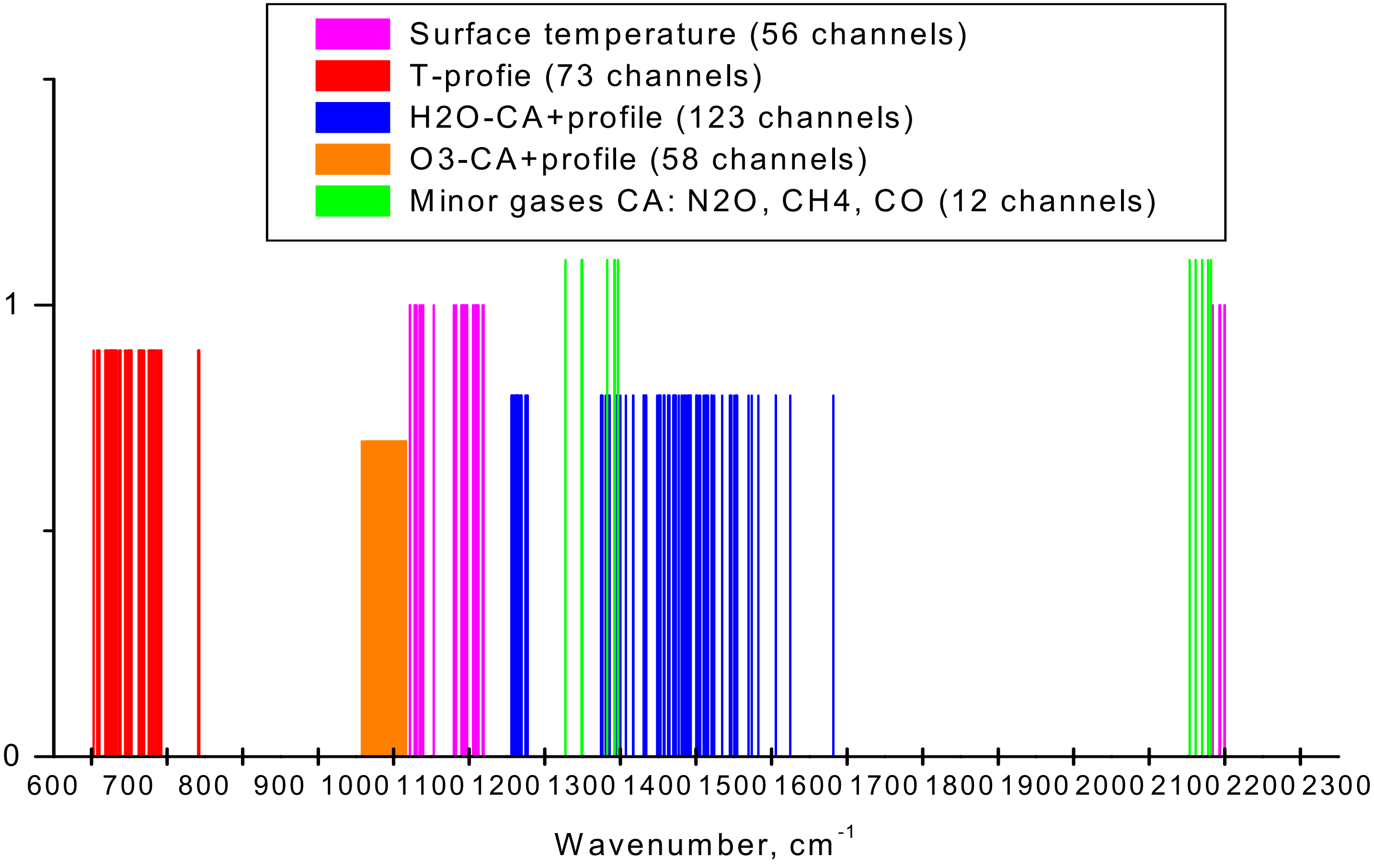


MPP retrievals	Target accuracy (r.m.s, per pixel)	Interfering factors to be *a priori* specified	*A priori* accuracy for interfering factors
Surface Skin Temperature	< 0.5-1.0 K	NO	-
Temperature profile	<1-2K / 1 km	NO	-
H2O total column	< 10 %	SST TP	< 1 K < 2K /km
H2O mixing ratio profile (troposphere)	< 20-30% / 2km		
O3 total column	<10 %	SST TP	< 1 K < 2K /km
O3 column 0-20 km	< 20 %		
O3 mixing ratio profile (20-40 km)	< 10 % / 1km		
CH4 total column	< 5 %	SST TP H2O (troposphere)	< 2 K < 2K /km < 30 % /2 km
N2O total column	< 10 %	SST TP H2O (troposphere) CH4 CA	< 2 K < 2K /km < 30 % /2 km < 10 %
CO total column	< 10 %	SST TP H2O (troposphere) O3 CA	< 2 K < 2K /km < 30 % /2 km < 10 %

Methods overview : MPP approaches selection

Parameter	Retrieval Method
Surface Skin Temperature	Physical inversion, no online RTM use
Temperature profile	Regression-type, “ridge” scheme
H2O total column & mix. ratio profile	Regression-type, PCR technique, direct SST and TP use
O3 total column & mix. ratio profile	1st-Stage: Regression-type, PCR technique, direct SST and TP use 2nd -Stage: Physical inversion (15channels), Online RT modeling
CH4 total column	Physical inversion, Online modeling (4 channels)
N2O total column	Physical inversion, Online RT modeling (3 channels)
CO total column	Physical inversion, Online RT modeling (5 channels)

Methods overview : Channels



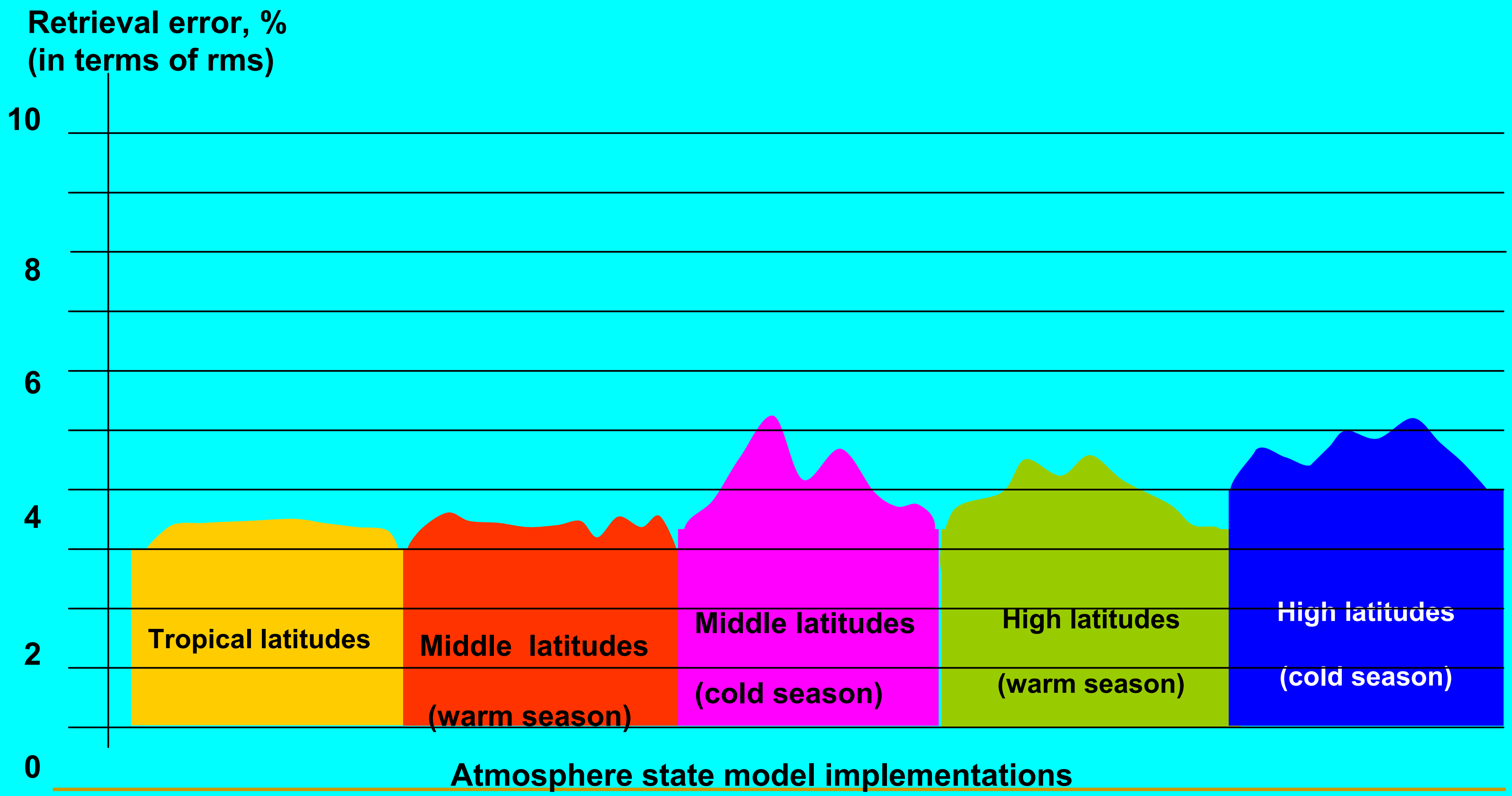
Achieved retrieval accuracies

MPP ACCURACIES: CH4 column amount (Clear Sky)

Range of CH4 column variation: from – 10% to +20 %

Sufficient accuracy (in terms of RMS) for supplementary T-q profiles retrieval : 2K and 30%, resp.

Sufficient accuracy (in terms of RMS) for supplementary N2O column retrieval: no requirement (!)

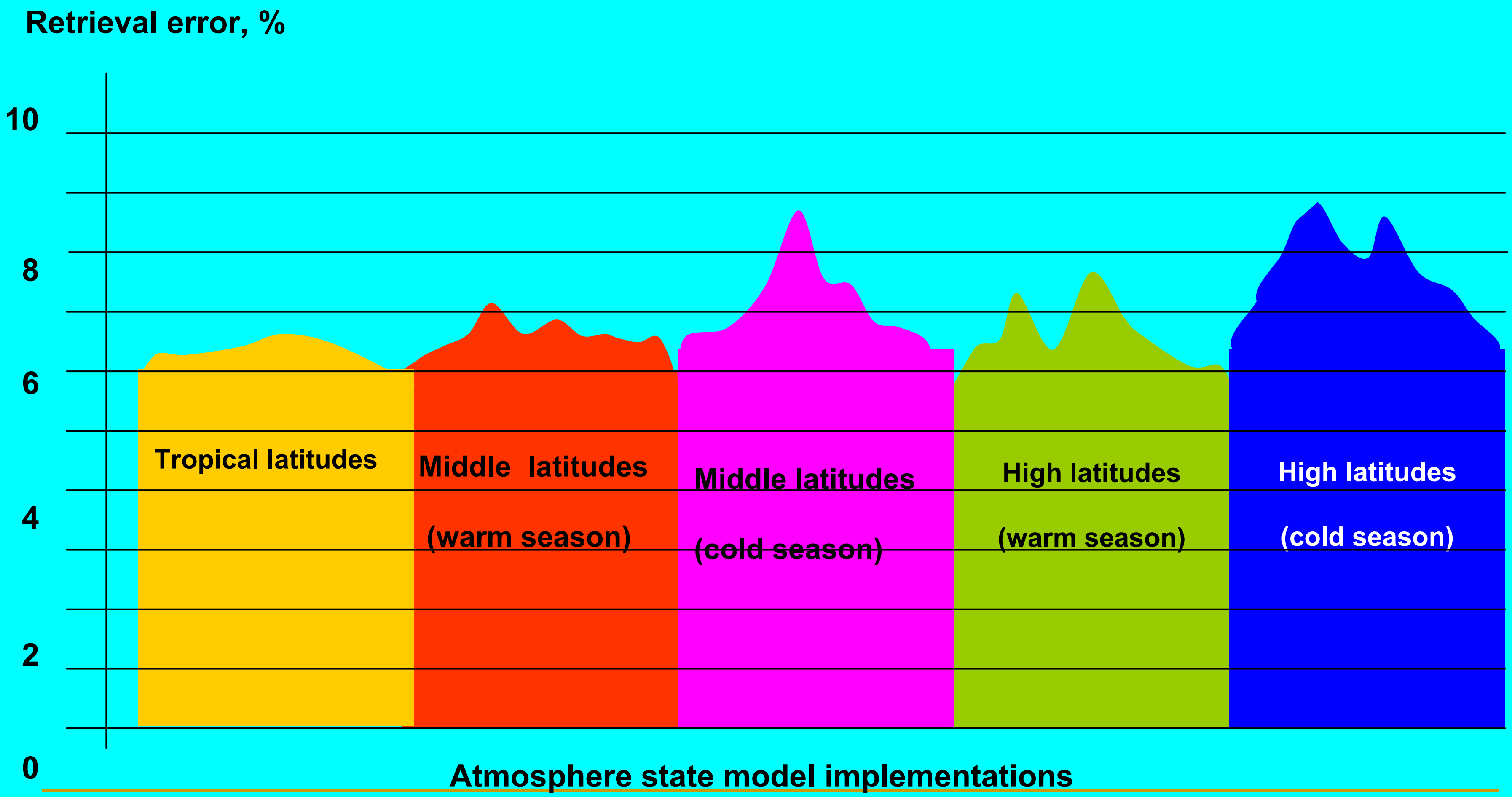


MPP ACCURACIES: N2O column amount (Clear Sky)

Range of N2O column variation: from – 10% to +20 %

Sufficient accuracy (in terms of RMS) for supplementary T-q profiles retrieval : 2K and 30%, resp.

Sufficient accuracy (in terms of RMS) for supplementary CH4 column retrieval: 5-10 %



CH4 column amount retrieval from IASI L1c measurements

1. The CH4 retrieval is carried out using 4 universal "static" IASI channels (i.e. independent on the lat/long zone and/or season): 1332.50, 1341.75, 1342.75 and 1346.75 cm-1
2. The level of retrieval accuracy for the clear-sky conditions is at least better than 5 % (in terms of the r.m.s. error) for all seasons and lat/long zones, as well as rather wide range of the column variation (from –10% to +30%).
3. The above rather high accuracy is achieved at moderate level of key interfering factors knowledge correspondent to the r.m.s. accuracy (for the 1 km troposphere resolution) of 2K and 30% for the temperature and the water vapor, respectively

N2O column amount retrieval from IASI L1c measurements

1. **The prior estimate of the CH4 with the accuracy at least not worse than 5% provides to reliably retrieve N2O column in the clear-sky conditions with the r.m.s. accuracy ranging (for different lat/long zones and seasons) from 4 to 9 %**
2. **The level of the a priory knowledge about the temperature and humidity can be at the same level as for the methane case providing the retrieval of the N2O relative variations about + 10-20 %. For lesser levels of variations the retrieval accuracy is slightly degrades for several very cold and dry atmospheres (to about 10%)**
3. **Absolutely robust and reliable N2O retrieval (within 4-9 % accuracy range) is available for all seasons and zones providing slightly better accuracy for the *a priory* T-q estimate, namely, 1.75 K and 25%, respectively.**
4. **The retrieval is reliably performed (in case of all lat/long zones and seasons) using three IASI channels, namely, those centered at 1277.25, 1298.50, 1299.50 cm^{-1}**

Effects of cloudiness in retrieving CH4 and N2O from IASI level 1c measurements

MOTIVATION:

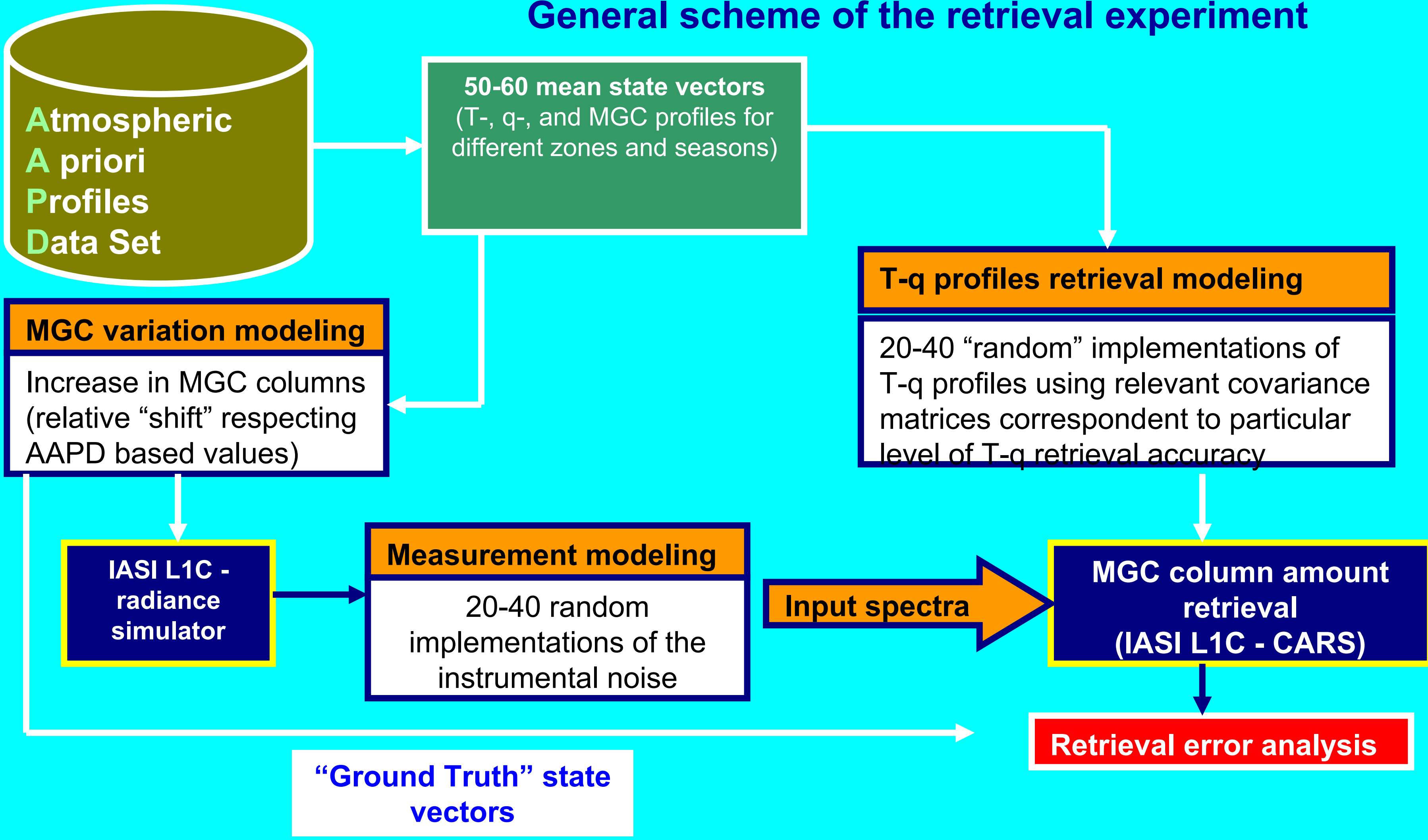
1. **Is it possible to retrieve trace gases columns from IASI measurements in case of partial or full cloud contaminated IFOV?**
2. **If it is possible to specify the limits for "applicable" cloudy situations and estimate the required accuracy level of the cloud parameters description**

EXPERIMENTS:

1. **Retrieval of the CH4 and N2O columns from the simulated IASI L1c measurements for characteristic sample of atmospheric situations (different lat/long zones, seasons, cloud coverage, cloud tops).**
2. **The retrievals have been performed in two "marginal" regimes:**
   - **a) the cloud parameters are specified accurately (referred to as "full cloud parameter correction")**
   - **b) the cloud contamination of the IFOV is not taken into account in retrieving columns (referred to as "no cloud parameters correction")**

CH4/N2O column amount retrieval from IASI: Effects of clouds

General scheme of the retrieval experiment



Atmospheric A priori Profiles Data Set

50-60 mean state vectors (T-, q-, and MGC profiles for different zones and seasons)

T-q profiles retrieval modeling

20-40 "random" implementations of T-q profiles using relevant covariance matrices correspondent to particular level of T-q retrieval accuracy

MGC variation modeling

Increase in MGC columns (relative "shift" respecting AAPD based values)

IASI L1C - radiance simulator

Measurement modeling

20-40 random implementations of the instrumental noise

Input spectra

MGC column amount retrieval (IASI L1C - CARS)

Retrieval error analysis

"Ground Truth" state vectors

MPP ACCURACIES: CH4 column amount (Effects of clouds)

ROOT MEAN SQUARE ERRORS (RMSE) of the CH4 column amount retrieval (+20% shift),

Case: Tropical latitudes

Full cloud parameters correction

R.M.S. error , in %
(Clear-sky case: 3.2 %)

Cloud Fraction

Cloud Top , in km

	0.1	0.2	0.3	0.5	0.7	1.0
1	3.2	3.2	3.2	3.2	3.2	3.2
2	3.2	3.2	3.2	3.2	3.1	3.2
3	3.2	3.2	3.2	3.3	3.3	3.5
5	3.2	3.3	3.4	3.3	4.4	5.4
7	3.3	3.5	3.8	5.3	6.4	9.1

No cloud parameters correction

R.M.S. error , in %
(Clear-sky case: 3.2 %)

Cloud Fraction

Cloud Top , in km

	0.1	0.2	0.3	0.5	0.7	1.0
1	3.2	3.2	3.2	3.2	3.2	3.2
2	3.2	3.2	3.2	3.2	3.1	3.1
3	3.1	3.1	3.0	2.9	2.8	2.9
5	2.7	3.4	5.7	NOR	NOR	NOR
7	4.5	9.8	NOR	NOR	NOR	NOR

RMSE < 10 %	10% <RMSE< 20 %	RMSE > 20 % or No retrieval

MPP ACCURACIES: N2O column amount (Effects of clouds)

ROOT MEAN SQUARE ERRORS (RMSE) of the N2O column amount retrieval (+20% shift),

Case: Tropical latitudes

Full cloud parameters correction

R.M.S. error , in %
(Clear-sky case: 5.5 %)

Cloud Fraction

Cloud Top , in km

	0.1	0.2	0.3	0.5	0.7	1.0
1	5.5	5.5	5.2	5.3	5.7	5.6
2	5.2	5.2	5.2	5.7	6.0	6.9
3	5.1	5.1	5.2	6.2	7.7	9.4
5	5.4	5.7	6.1	8.2	10.3	15.6
7	5.6	5.7	6.3	8.6	13.1	24.4

No cloud parameters correction

R.M.S. error , in %
(Clear-sky case: 5.5 %)

Cloud Fraction

Cloud Top , in km

	0.1	0.2	0.3	0.5	0.7	1.0
1	5.2	5.4	5.9	6.6	7.1	8.2
2	6.2	8.2	9.9	13.5	18.7	NOR
3	7.1	10.0	13.3	20.4	NOR	NOR
5	11.3	21.0	30.4	NOR	NOR	NOR
7	18.8	NOR	NOR	NOR	NOR	NOR

RMSE < 10 %	10% <RMSE< 20 %	RMSE > 20 % or No retrieval

Trace gases retrieval: Conclusions

1. **The retrieval of both the CH4 and N2O columns is reliably possible for rather wide range of cloudy situations providing high-accuracy knowledge on key cloud (bulk) parameters such as the cloud top height and the cover fraction**

2. **Ignoring of the cloud contamination correction is feasible (i.e. provides reasonable column retrieval accuracy) for the case of CH4 within the following cloud parameters limits:**

   H = 1 – 2 km ; fractions = 0.1 - 1.0

   H = 3 – 5 km ; fractions = 0.1 - 0.3

   H > 7 km ; fractions <= 0.1

3. **Ignoring of clouds for the case of N2O retrieval is possible only for low-level clouds (1-2 km) and low cover fractions (about 0.1 – 0.2)**

4. **The "feasibility limits" of cloud contamination ignoring are valuably wider for sufficiently wet and warm atmospheres (tropics, middle latitude summer time) for both the CH4 and N2O retrieval**

Towards estimating the column amounts of atmospheric CO2 over boreal forests from AIRS/Aqua

- **CO2 related issues**
- **Sensitivity studies**
- **AIRS channel selection for detecting CO2 variations**
- **Retrieval of atmospheric CO2 column amounts**
- **Validation exercise**

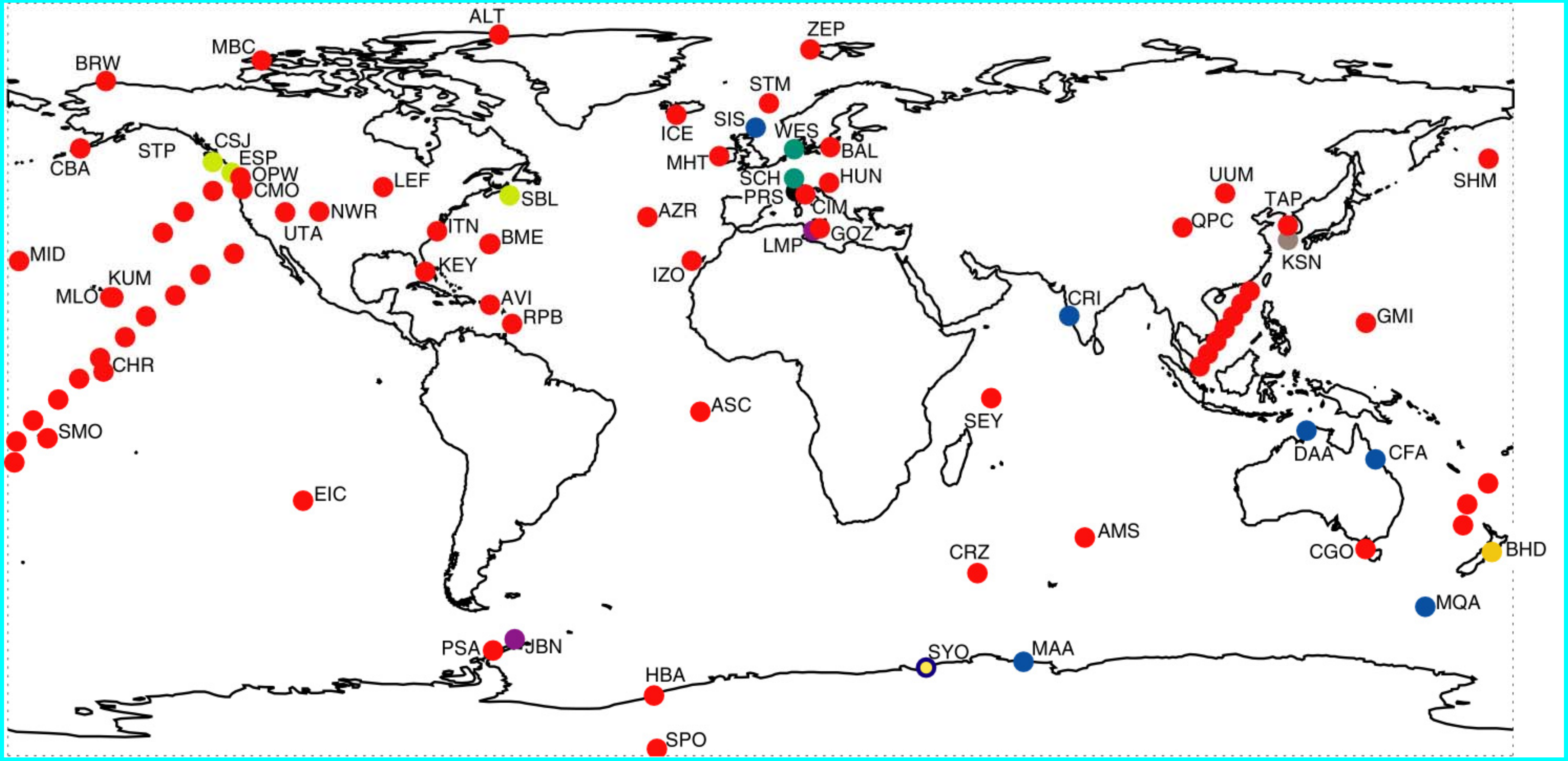
These studies have been financially supported by ESA/IAF (GMES Project “Development of novel techniques for CO2 retrieval…”).

CO2 related issues

… " consistent, very carefully calibrated studies of atmospheric CO2 are needed over long time periods to determine if, as suggested by data from recent year, CO2 growth rates and/or airborne fractions are increasing, or if there has been a shift in the land/ocean balance"

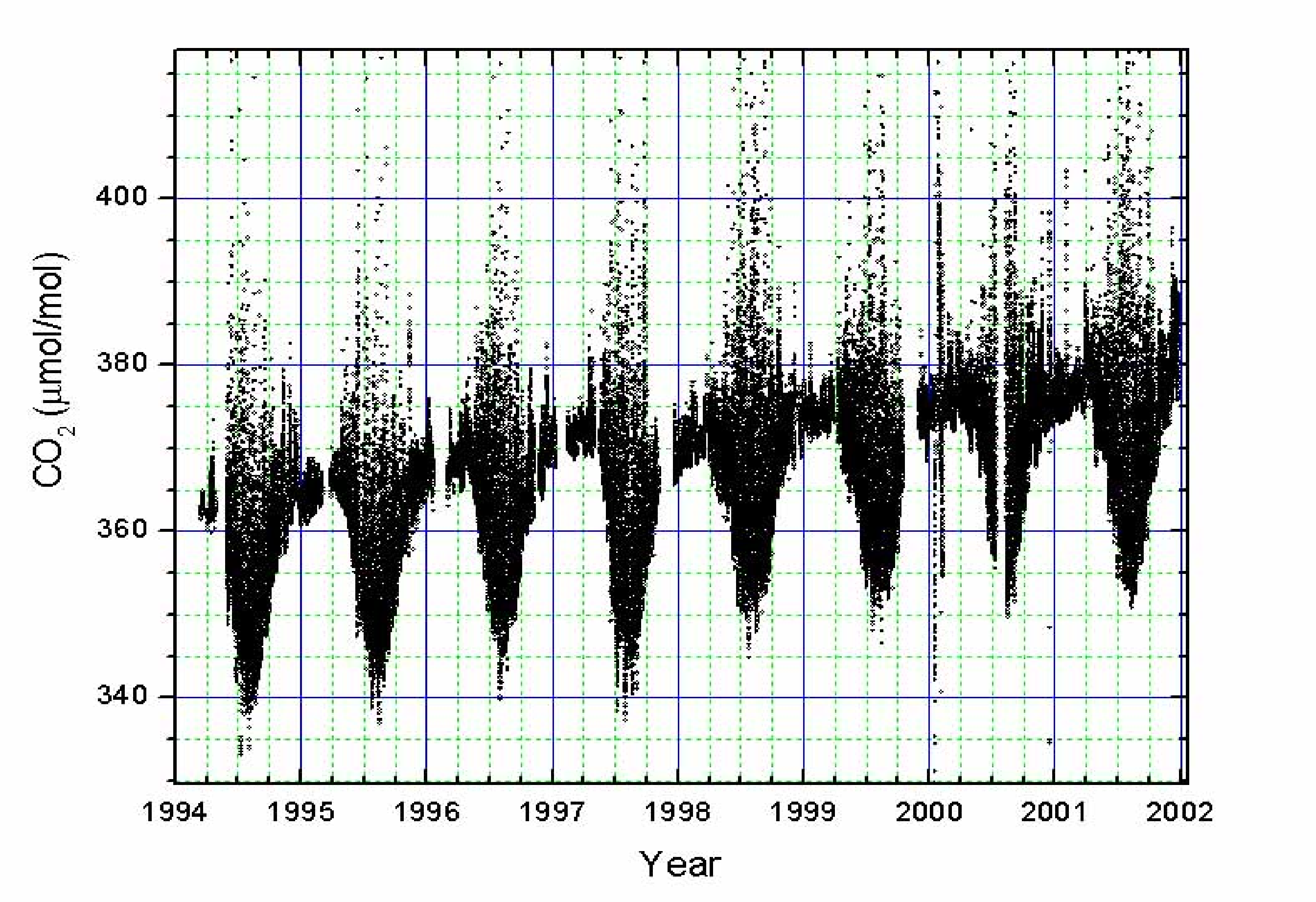
(International Panel on Climate Change, 2006).

Flask Sampling Networks. GlobalView 2000 (source: G.L.Stephens, R.Engelen)



CO_2 in the atmosphere

CO2 is no longer considered as uniformly mixed gas !
Instead, the goal is to determine small spatial regional variations of CO2



Annual cycle of CO2 near-surface concentration BOREAS region (Canada).
How far this variability goes in the atmosphere ?

Source:
A.Trishchenko

Satellite CO_2 observations (atmosphere)

- Solar region

  SCIAMACHY/ENVISAT is the only sensor currently available

  Future Orbiting Carbon Observatory (OCO), GOSAT

  New planned missions (Canadian GGAS -FTS, MEOS …)
- Thermal region

  AIRS/Aqua

  Forthcoming IASI/METOP

  some other sensors (IRFS-METEOR,CrIS/NPOESS,…)

Examples of CO2 airborne observations

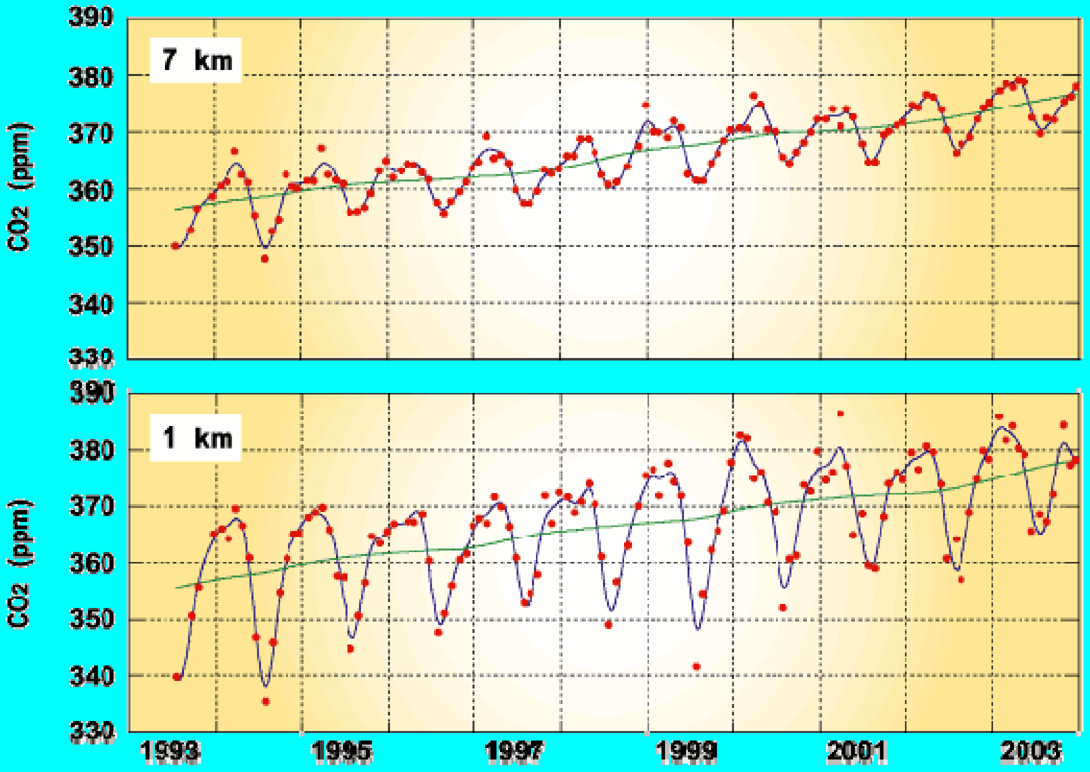
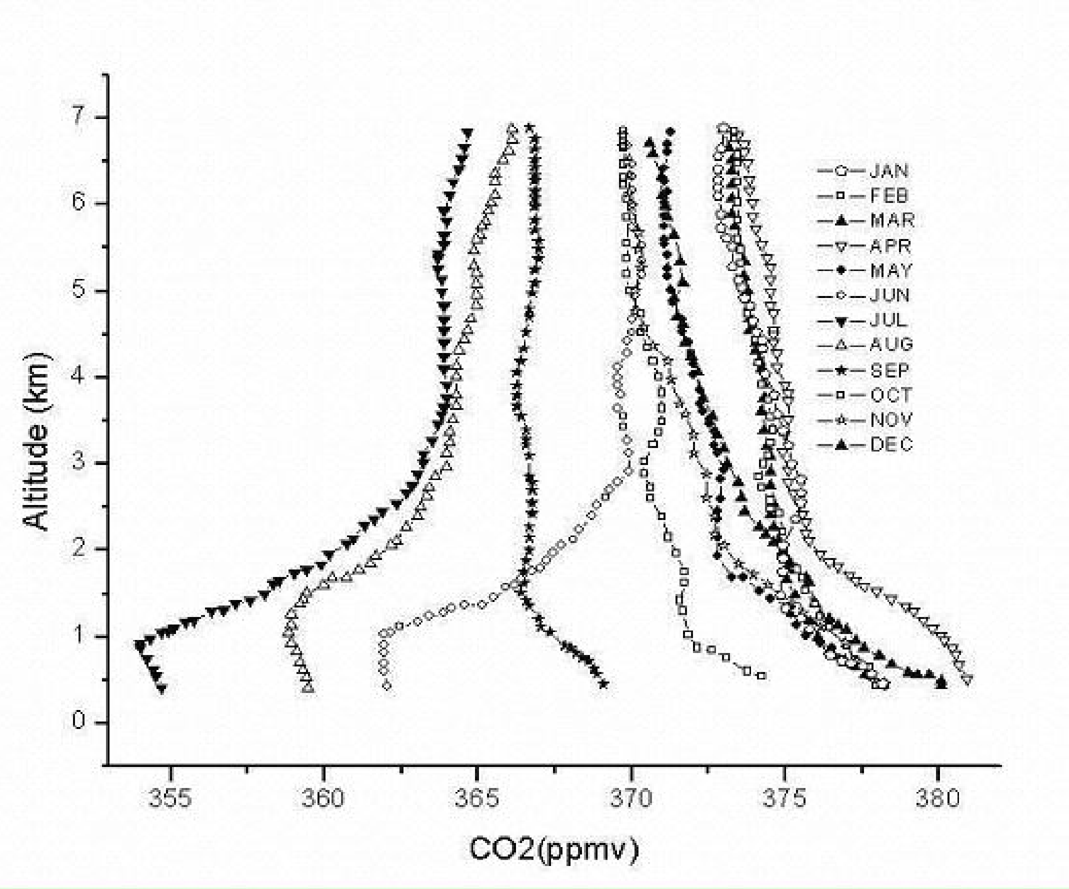
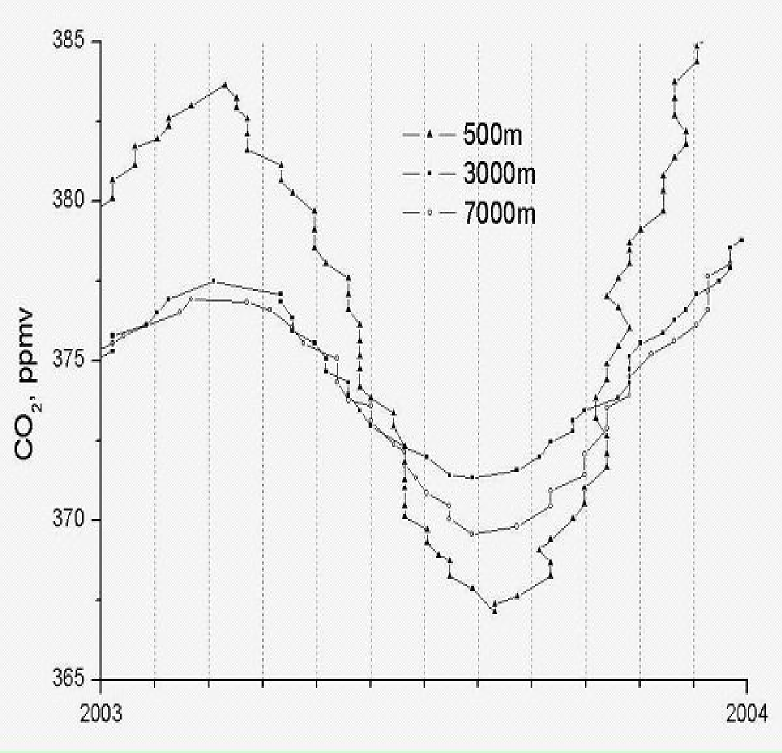


Figure 3. Time series of CO_2 concentration at 1 km and 7 km altitudes over Surgut

Note: Solid circles, blue lines, and green lines represent the observed data, the best-fit curves, and the long-term trends, respectively.

Vertical structure and seasonal cycle of CO2 over Siberian boreal zone





aicraft observations (Arshinov et al ., 2005; Zuev et al., 2005)

Regional differences, amplitude of seasonal and diurnal cycle of CO2 in the boundary layer can be very large (from 10-15 ppmv to 40-60 ppmv);

Variability reduces with altitude, but still can be substantial (>5ppmv) up to the heights in the upper troposphere and over synoptic spatial scales.

Critical Issues

1. **Retrieval of CO2 column amount (CA) or profiles (CO2(p)) from atmospheric IR sounders data is problematic since the IR channels sensitive to CO2 variations are also sensitive to temperature variations and the presence of clouds. Moreover the temperature and cloud variations should be treated as the main interfering factors. To advance the remote sensing methodology for monitoring CO2 concentration from advanced IR sounders data means separating these effects.**

2. To address this issue the studies have been focused on the selection of sub-sets of the dedicated AIRS super-channels. The objective of super-channel sub-sets selection is to reduce the effect of temperature profile uncertainties (key interfering factor) on the accuracy of trace gas CA retrieval. The signal in the dedicated super-channel (constructed as linear combination of pre-selected individual channels) should be sensitive to trace gas CA variations and should have small sensitivity to T(p) variations.

Procedures of AIRS data inversion and estimating CO2 column amounts

Two approaches are appears to be suitable for AIRS data inversion:

- concurrent retrieval of “full” state vectors (incorporating some parameters relating to CO2 abundance);

- self-dependent (or stand alone) retrieval of CO2 abundance characteristics (using ancillary information, e. g. extracted from the same AIRS data).

• The second approach has the advantage that it should be more flexible and less complicated.

Methodology

- **The approach to CO2 concentration detection includes:**

- **collecting a dataset with representative samples of atmospheric state vectors and high resolution thermal infrared satellite measurements (AIRS) – these may be real or simulated via an adjusted Fast Radiative Transfer Models;**

- **analysis of the satellite measurement information content with respect to CO2 perturbations and selection of dedicated AIRS channel subsets (to minimize interference from temperature and cloud effects);**

- **developing, testing, and validating the procedure for retrieval carbon dioxide CA (using synthetic or real satellite data).**

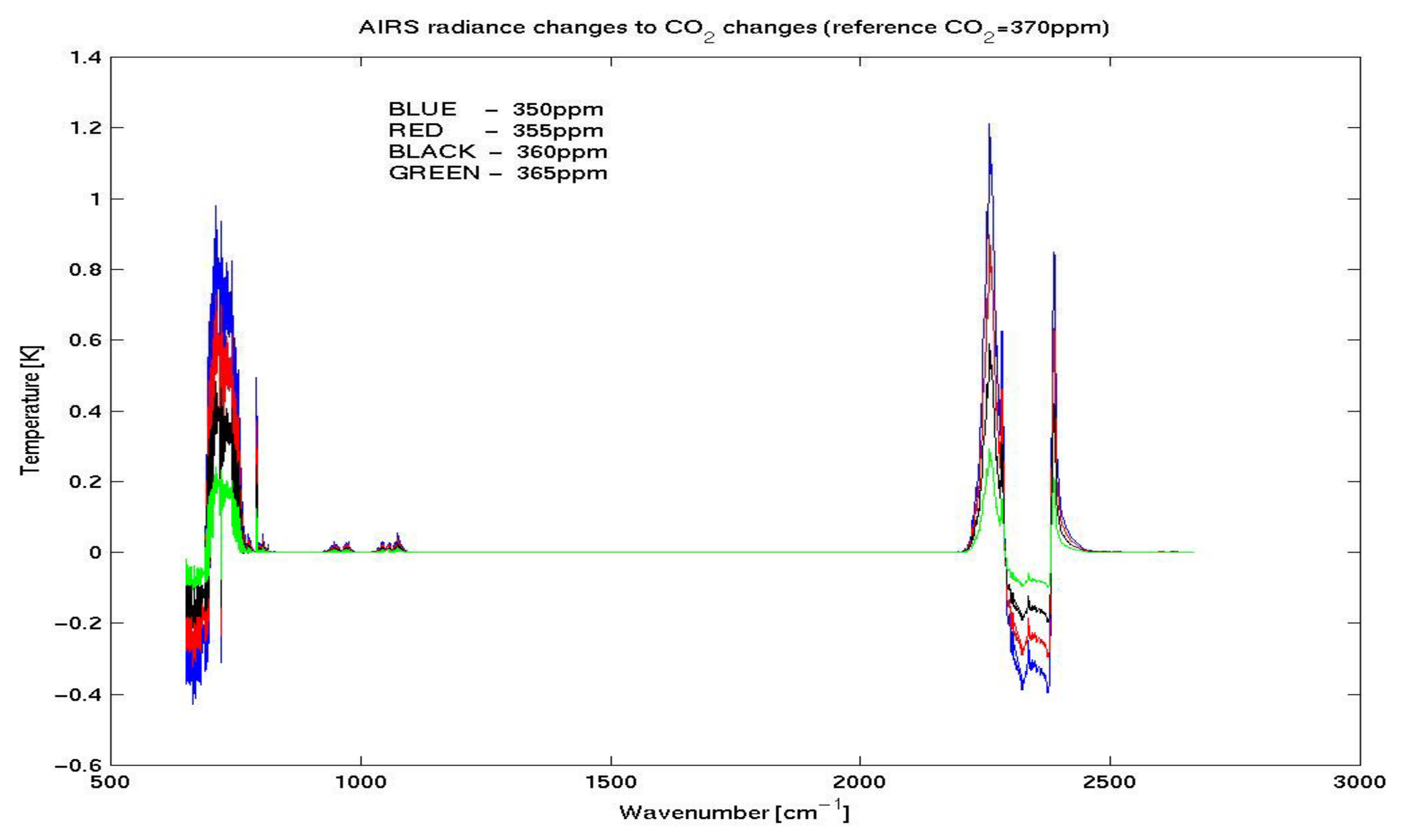
Initial dataset

- To generate a simulation dataset, one needs a representative sample of atmospheric state vectors that include the associated CO2 CAs and/or vertical profiles. Various datasets can be utilized for compiling sample atmospheric state vectors, in particular, UKMO analysis data. In our studies we used two typical CO2 vertical profiles extracted from (Schmidt et al., 1991) and complemented below 600 hPa by data from other sources. Some calculations and experiments have been performed using carbon dioxide profiles with constant mixing ratios and CAs (in the range of 350-380 ppmv).
- A sample of in-situ airborne CO2 observations (over the area of boreal forests-Novosibirsk region as well as over Surgut region) was utilized in the validation exercise.
- The maximum CO2 seasonal variability (about 16 ppmv) is expected at northern mid-latitudes between April and August. The variations of CO2 CA in the range 5-15 ppmv were chosen in our studies.

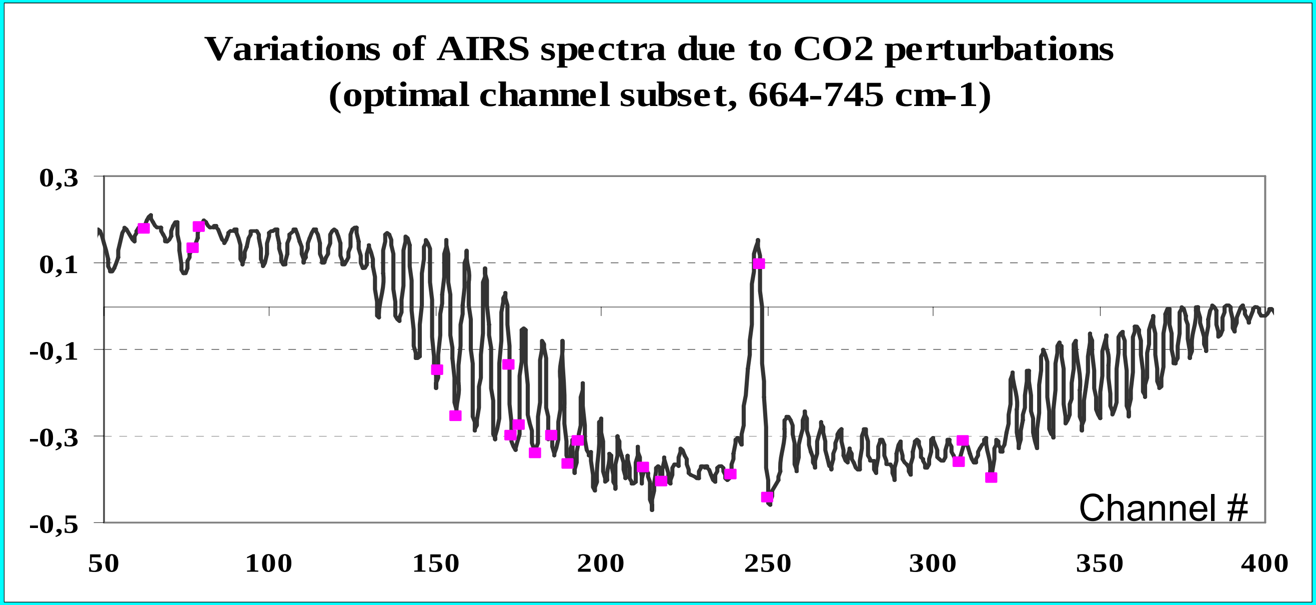
Fast Radiative Transfer Model for simulating AIRS data

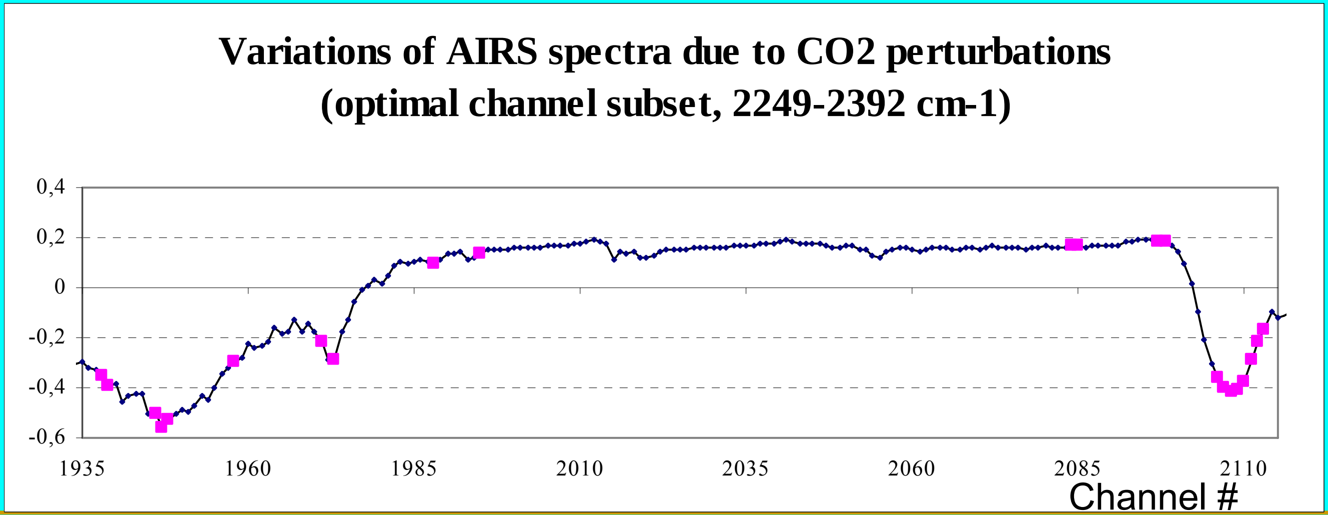
Upon investigating SARTA (Stand alone AIRS Radiative Transfer Algorithm) from (Strow et al., 2003), we found the option to adjust CO2. At CIMSS the SARTA code has been implemented and modified by Yu. Plokhenko to accommodate changing CO2 profiles. Later on the modified version of SARTA has been implemented at SRC “Planeta” (on a Windows platform) and used for modeling AIRS measurements and for conducting sensitivity studies.

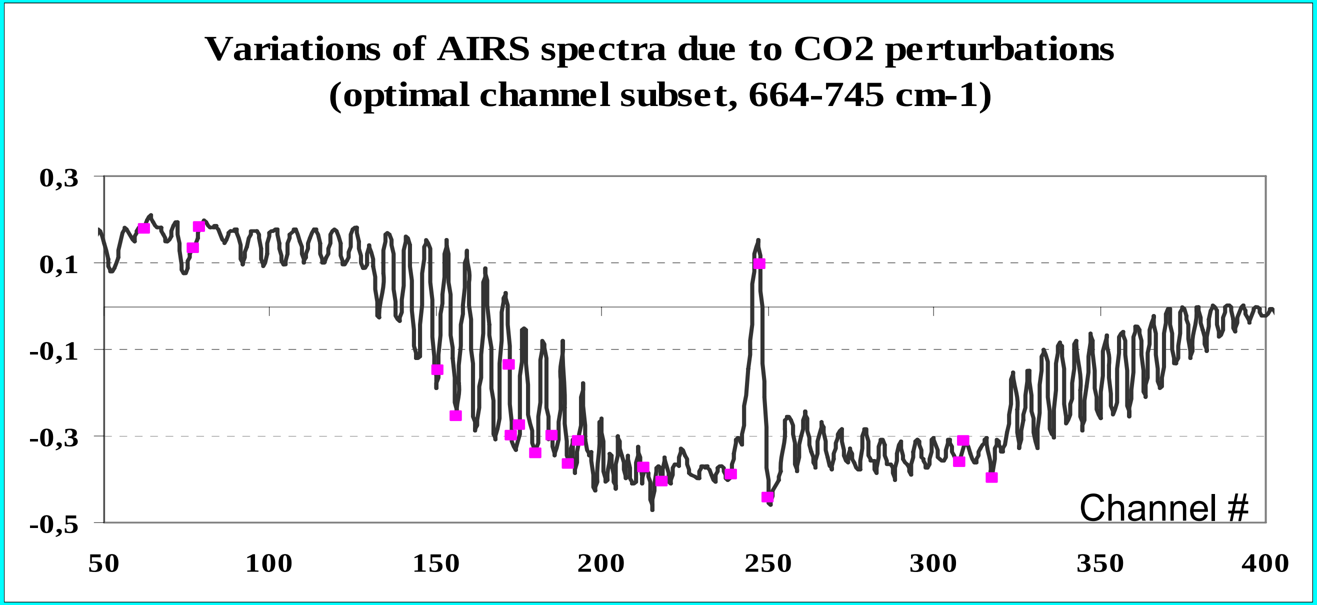
Sensitivity Studies



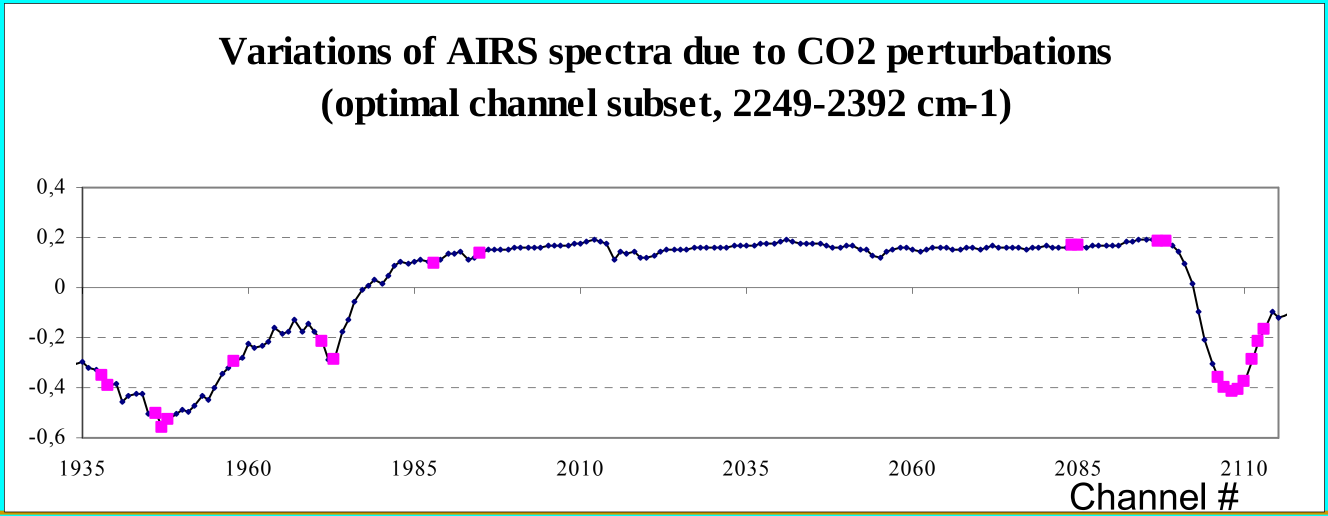
The AIRS spectrum (between 500 and 3000 cm-1) of brightness temperature changes calculated with SARTA in response to decrease in total CO2 from 370 ppmv to 350 ppmv (blue), to 355 ppmv (red), to 360 ppmv (black), and to 365 ppmv (green). The linearity of the response is evident.


Variations of AIRS spectra due to CO2 perturbations
(optimal channel subset, 664-745 cm-1)
0,3
0,1
-0,1
-0,3
-0,5
50
100
150
200
250
300
350
400
Channel #


Variations of AIRS spectra due to CO2 perturbations
(optimal channel subset, 2249-2392 cm-1)
0,4
0,2
0
-0,2
-0,4
-0,6
1935
1960
1985
2010
2035
2060
2085
2110
Channel #



Variations of AIRS spectra due to CO2 perturbations
(optimal channel subset, 664-745 cm-1)



Variations of AIRS spectra due to CO2 perturbations
(optimal channel subset, 2249-2392 cm-1)

Approach to retrieval CO2 CA

- **It is necessary to specify channels with identical (or almost identical) and strongly differing response to T(p) and CO2 variations respectively (temperature- and CO2-dedicated).**

Building of super-channels

1) Selection of T- and CO2 -dedicated channels with “similar” temperature Jacobians or weighting functions HT; signals in one T-and several CO2-dedicated channels are designated as TB(I) and TB(II), TB(III),… respectively.

2) Specification of “synthetic” channel with signal TB(synth) as linear combination of two or more CO2-dedicated channels (signals TB(II), TB(III), TB(IV),…) and with temperature Jacobian, close to the Jacobian of T-dedicated channel. Signal in the synthetic channel is formed using least square fitting: TB(synth) = K1 TB(II) + K2 TB(III), where K1, K2 are derived as solution of extremal problem:

$$\min J_W(K_1,K_2)=\sum_i [H_{T.I}(p_i) - H_{T.synth}(p_i)]^2, \quad H_{T.synth}(p) = K_1 H_{T.II}(p) + K_2 H_{T.III}(p).$$

3) Derivation of super-channel with signal TB (sc) = TB (I) – TB (synth).

Building of super-channels

TB(sc) = TB.0(sc) + δT TB(sc) + δq TB(sc) + δOz TB(sc) + TB(sc) + ε, (1)

where:

δT TB(sc) = (HT.I – HT.synth) ΔT,

δq TB(sc) = (Hq.I – Hq.synth) Δq,

δOz TB(sc) = (HOz.I –HOz.synth)$\cdot\Delta$Oz,

TB(sc) = (HQ.I – HQ.synth) ΔQCA,

TB.0(sc) is modeled signal calculated for vector **x0**; the temperature and other Jacobians are also calculated for **x= x0**.

Terms δT TB(sc), δq TB(sc), δOz TB(sc) from (1) present input of variations T(p) and other interfering factors into signal variations ΔTB(sc) = TB(sc) – TB.0 (sc).

Variations |TB(sc)| should exceed notably variations |δT TB(sc)| as well as should exceed the instrumental noise.

METHOD OF AIRS DATA INVERSION

Formulae (*) can be presented as follows:

$\Delta TB(sc) = \kappa 1 + \kappa 2\ \Delta QCA + \varepsilon$,

where $\kappa 1 = \delta T\ TB(sc) + \delta q\ TB(sc) + \ \ TB(sc)$, $\kappa 2 = HQ(sc)$

Linear relationship between ΔQCA and measurements (variations $\Delta TB(sc)$ or $\Delta(sc)\ \ $) leads to the following regression estimator for ΔQCA :

$\Delta QCA(regr) = C1\ \Delta TB(sc) + C2$,

where C1, C2 – const are regression coefficients.

There are two options:

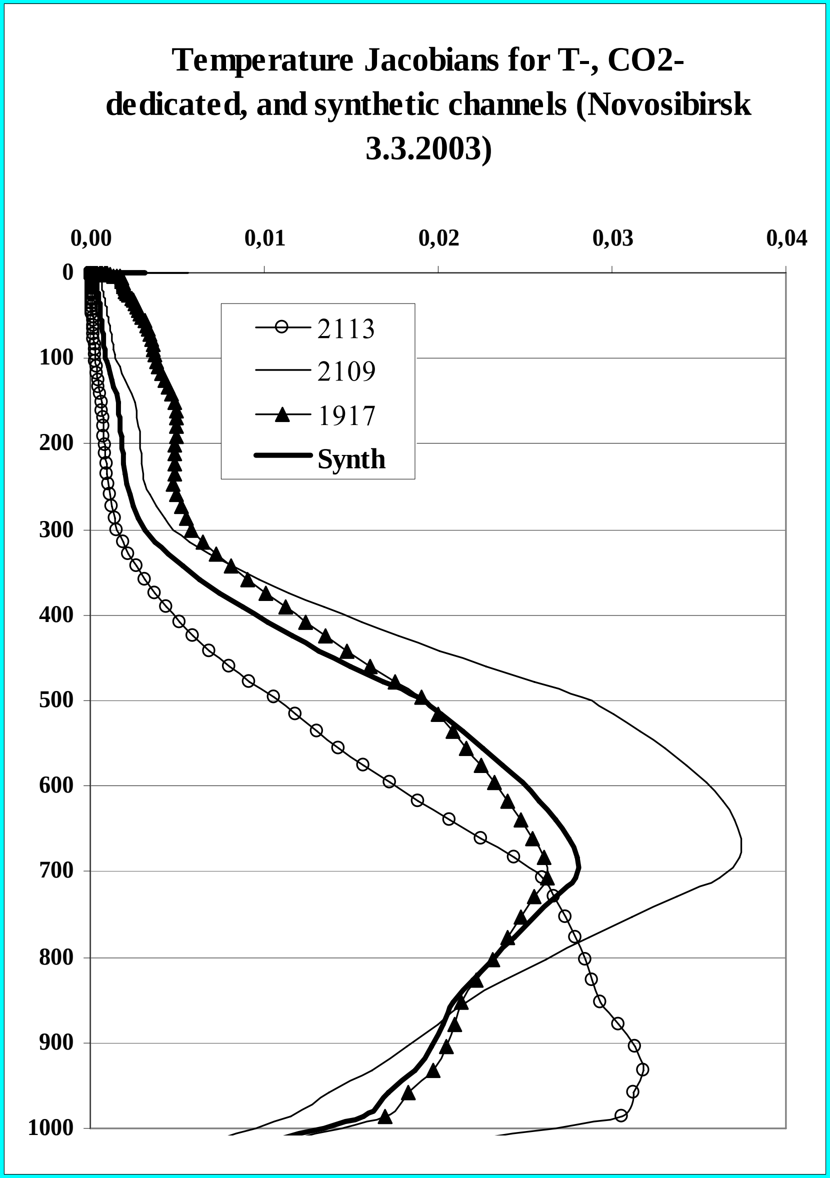
- **Synthetic regression-**training sample is compiled using modeled AIRS data for various CO2 CA-s
- **Empirical regression-** training sample is compiled using collocated actual AIRS data and *in-situ* (airborne) CO2 observations

SUPER-CHANNEL FORMATION FOR CO2 CA RETRIEVAL

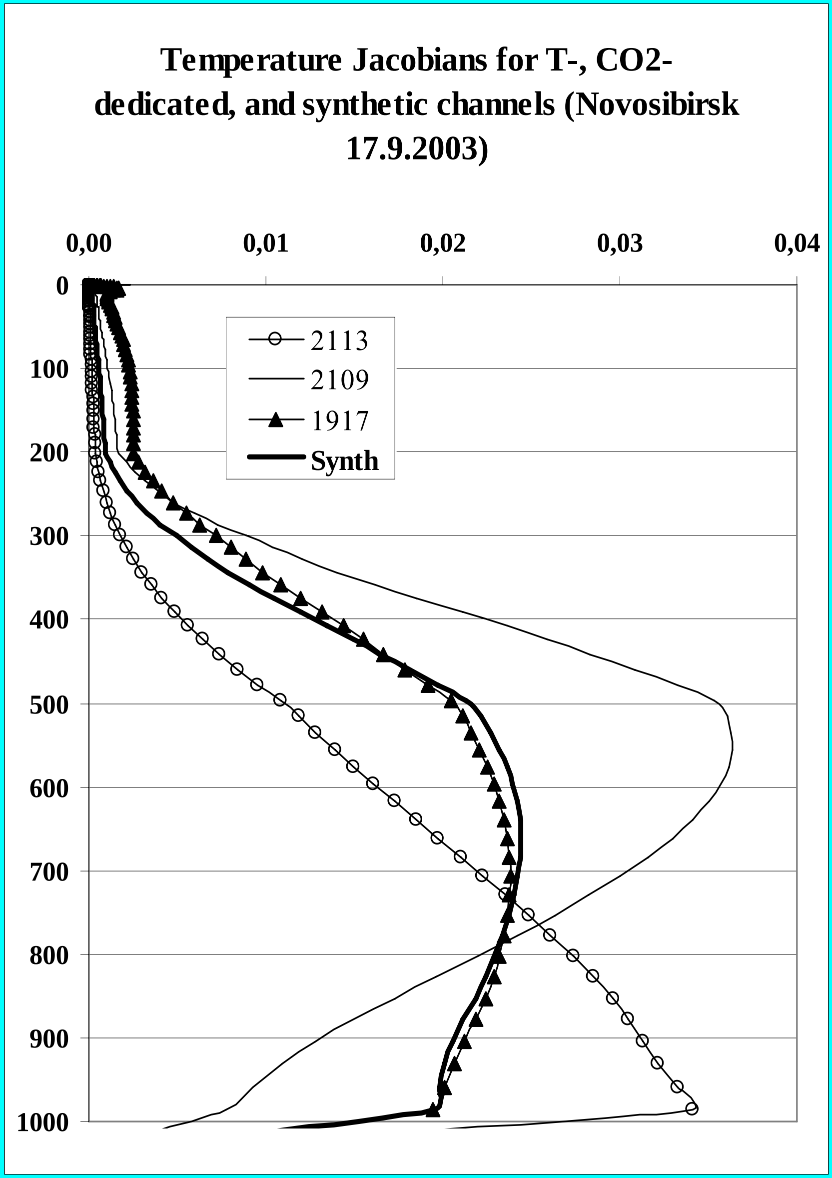
- T-dedicated channel : #1917 at 2229.6 cm-1;

- CO2-dedicated channels: #2109 at 2388.2 cm-1 and # 2113 at 2392.1 cm-1;

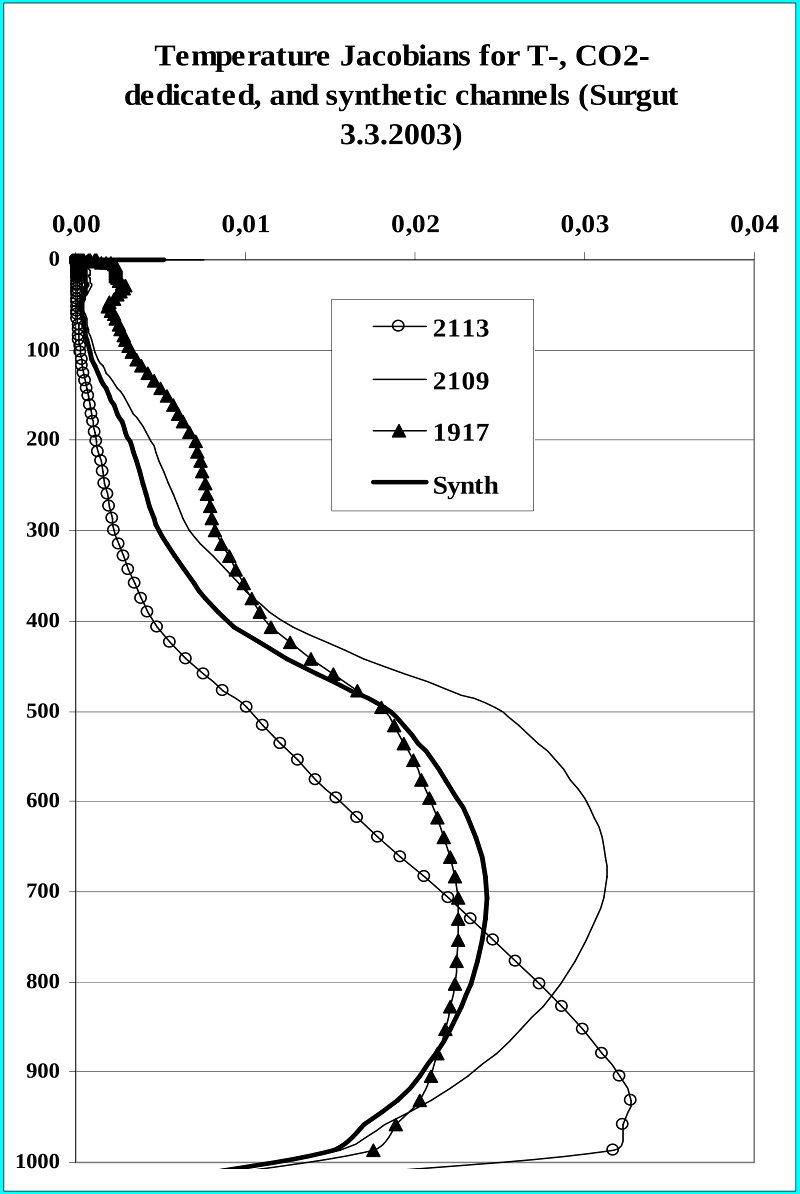
- TB(synth)=0.498 TB(2109) +0.426 TB(2113)
- TB(sc) = TB(1917) – TB(synth).



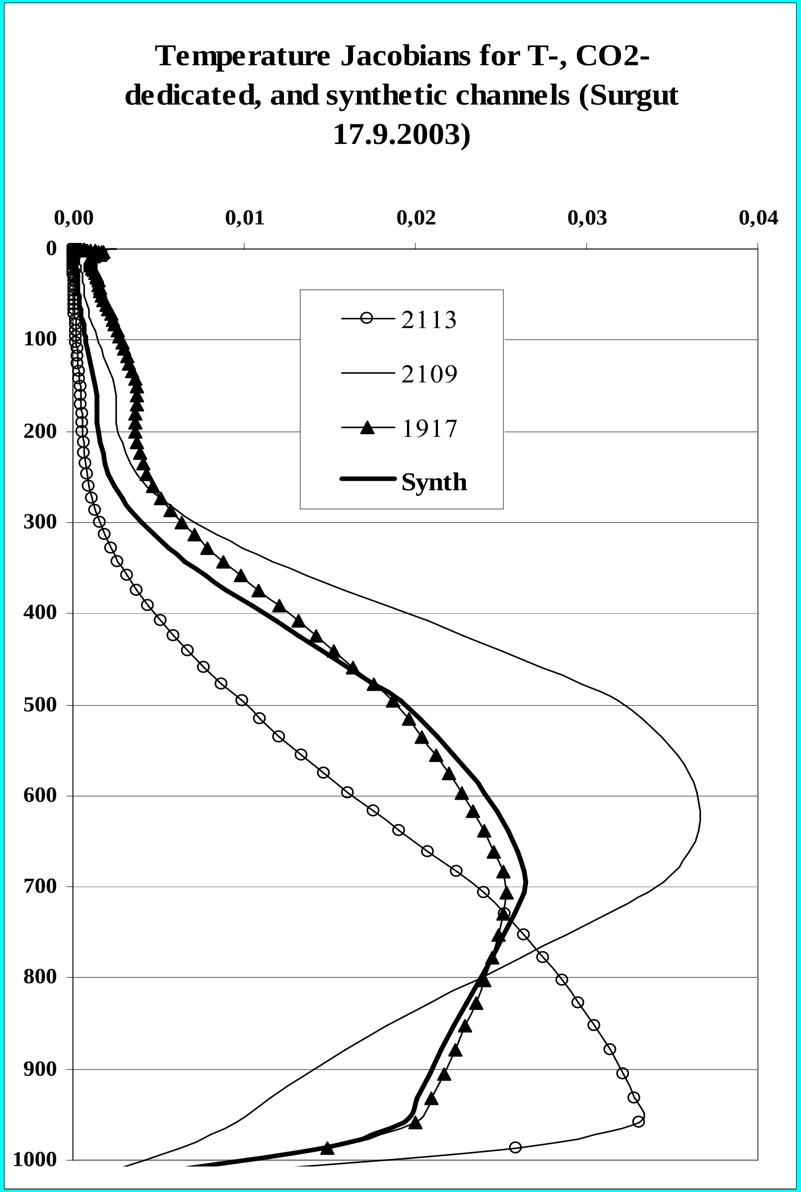
Temperature Jacobians for T-, CO2-dedicated, and synthetic channels (Novosibirsk 3.3.2003)



Temperature Jacobians for T-, CO2-dedicated, and synthetic channels (Novosibirsk 17.9.2003)

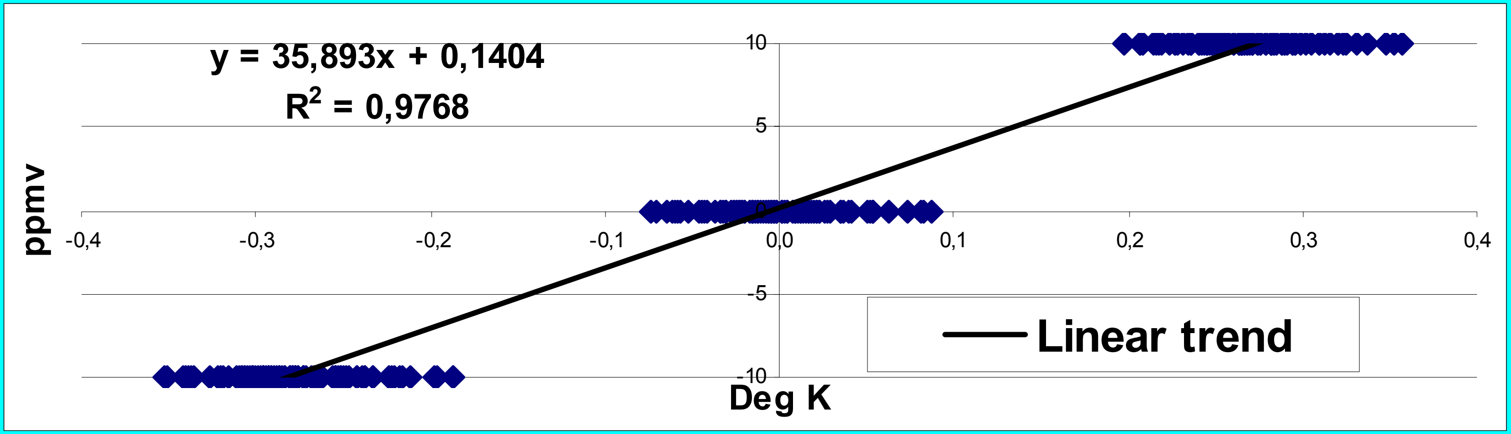


Temperature Jacobians for T-, CO2-dedicated, and synthetic channels (Surgut 3.3.2003)



Temperature Jacobians for T-, CO2-dedicated, and synthetic channels (Surgut 17.9.2003)

Synthetic Regression



Error statistics for Q_{CA} retrieval (synthetic AIRS measurements, 2500 implementations)					
ppmv	**360**	**365**	**370**	**375**	**380**
BIAS	**0,06**	**0,04**	**-0,04**	**0,11**	**0,14**
R.M.S.E.	**2,11**	**2,07**	**1,98**	**2,00**	**2,03**

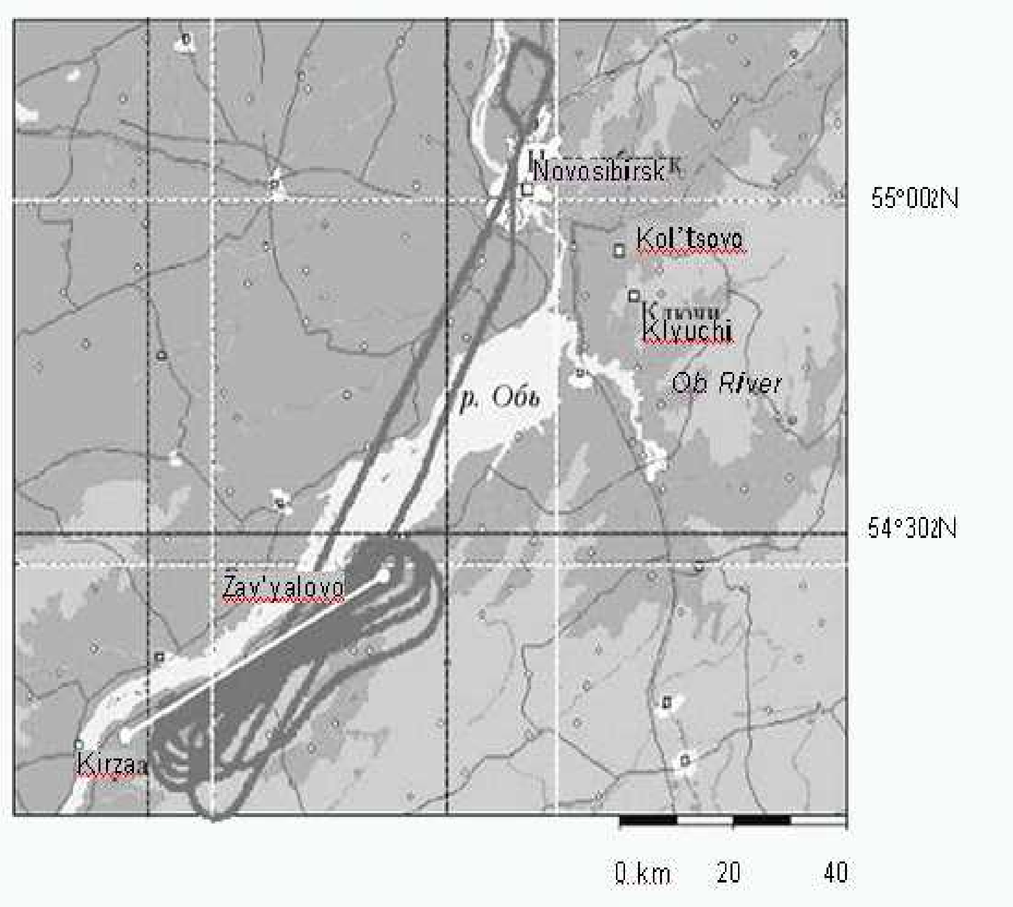
Validation of the AIRS-based mid-tropospheric CO2 CA retrievals over Siberian boreal forests

The series of retrieval experiments has been conducted for a sample of more than 10 granules of real AIRS measurements. It was found to be suitable to use the results of airborne measurements that have been performed within the framework of a joint Japanese-Russian Project, see e.g. (Arshinov et al., 2005). Regular measurements of the CO2 concentration have been carried out since 1997 till now with the use of an Antonov-30 flying laboratory. The region of airborne surveys and the flight routes are located at the right bank of the southern part of the Ob Reservoir. The area of airborne measurements covers the region 54°08’-54°33’ N, 81° 51’-82°40’ E, moreover the boreal area consists 90% of coniferous trees. At the end of each month the ambient air is flask- sampled at heights of 0.5, 1, 1.5, 2, 3, 4, 5.5 and 7 km.

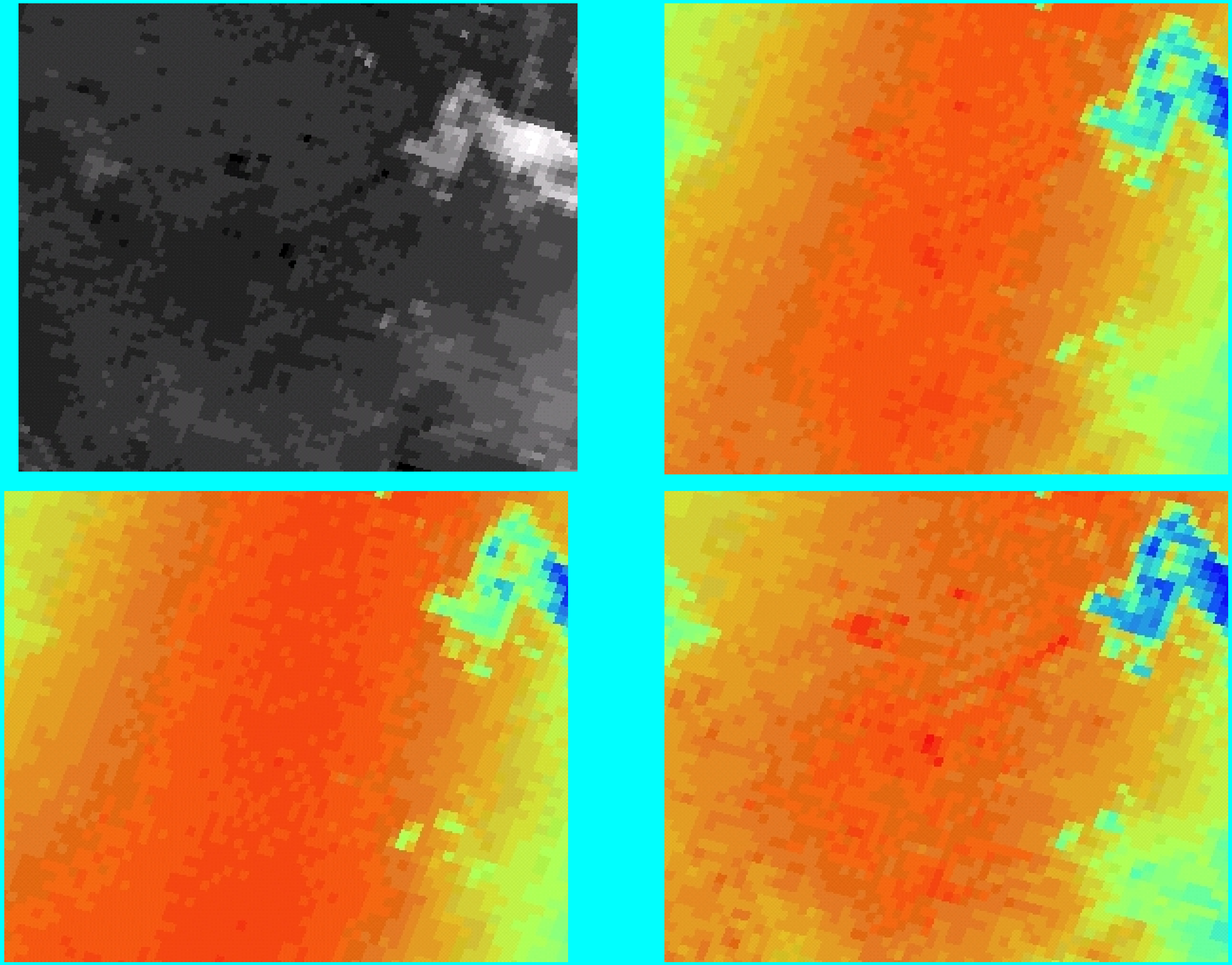
Along with this the similar experiments have been conducted for the Surgut region (60-62° N, 70-75° E).

Validation exercise for Novosibirsk region

Real AIRS data, namely granules with Cloud-cleared radiances for pre-selected area and time period between January and December 2003 (for one-two dates of each month) have been downloaded through http://daac.gsfc.nasa.gov/data/dataset/AIRS/02_L2_Products/index.html. The atmospheric T- and q-profiles (components of state vectors) for the same area and time period have been extracted as already mentioned from the UKMO (Bracknell) analysis and complemented by results of airborne CO2 measurements



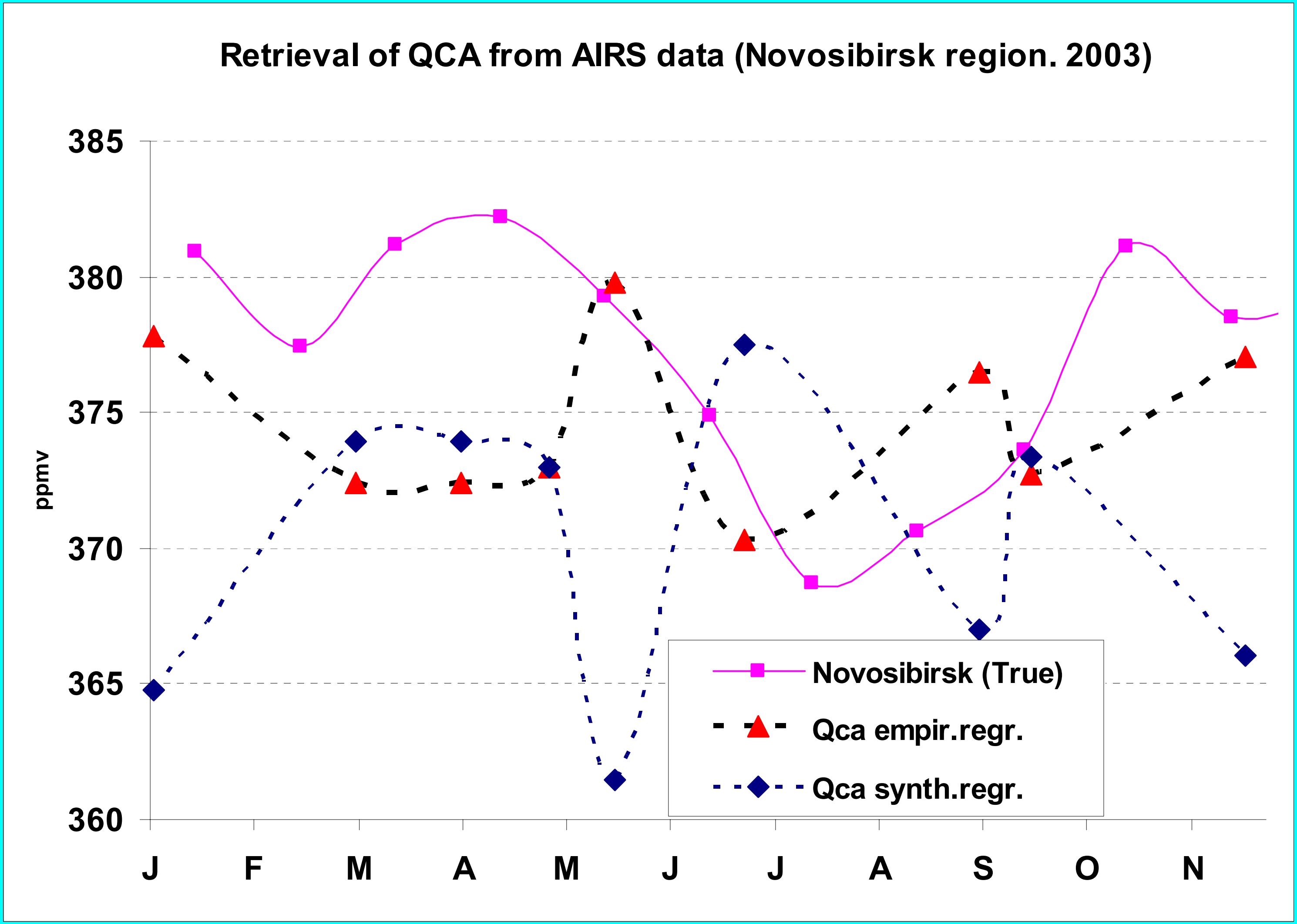
Flight route over region of interest



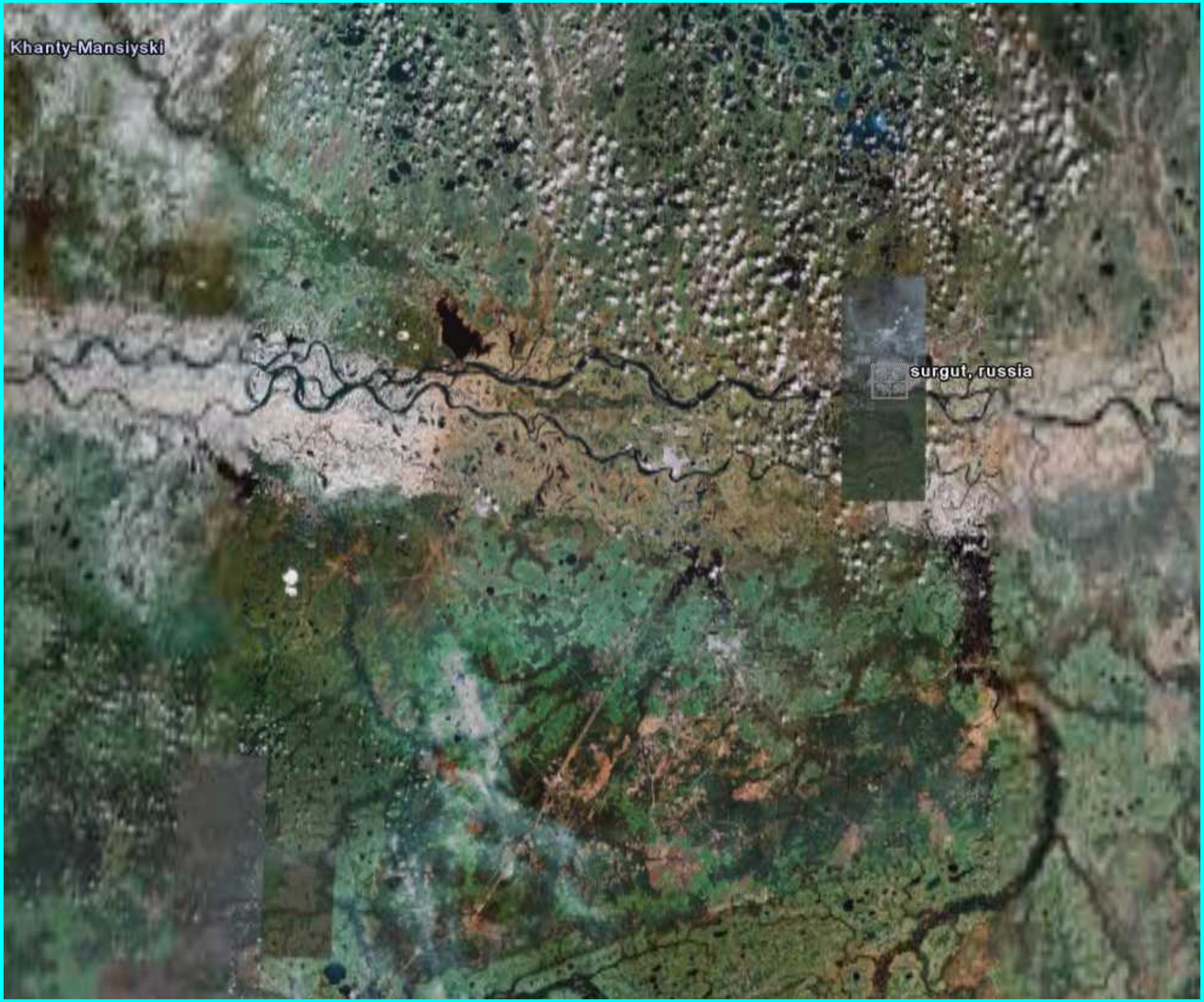
Display (in HYDRA) of AIRS radiances in channels at 917.2, 2229.6, 2388.2, 2392.1 cm-1 for the Novosibirsk region, 25 June 2003

Novosibirsk region

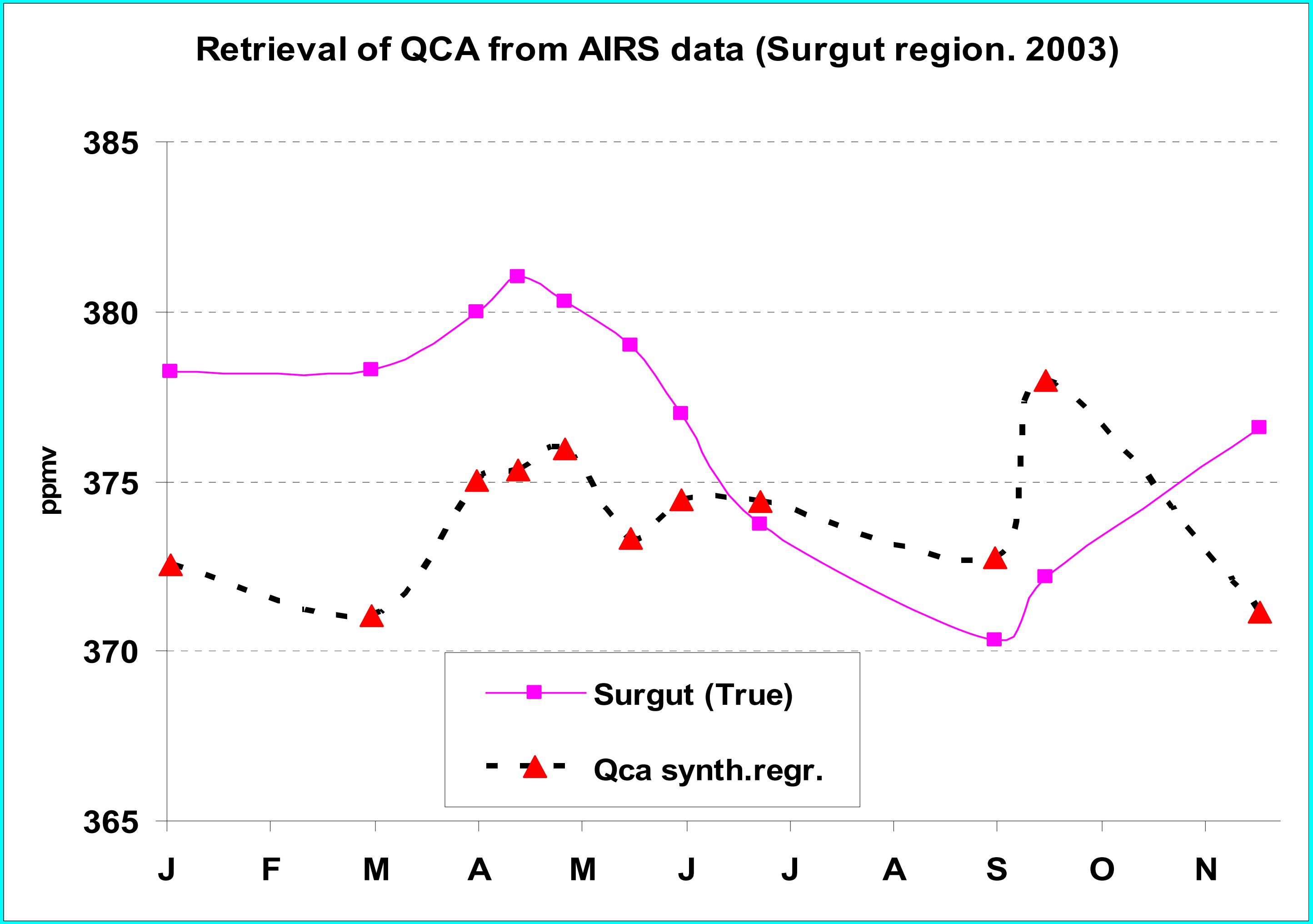
Results of validation exercise (actual AIRS data)



Surgut region



Results of validation exercise (actual AIRS data)



Concluding remarks

The following developments are proposed to improve retrievals:

- **The creation of a data set of CO2 mixing ratio profiles (from in situ airborne observations) representative of actual variability for different regions over boreal forests and complemented by co-located satellite measurements (AIRS, IASI) and atmospheric state vectors;**
- **The development and testing of the empirical and the synthetic regression estimators;**
- **The examination of the behavior of retrieval errors as a function of regression type, season, geography, and the number of pixels to be averaged in space and time (while applying the regression algorithm);**
- **The refinement and extension of the regression algorithm of CO2 retrieval through more representative validation (involving more complete training/testing samples). Using the regression estimate as the first guess in the method of the retrieval of “full state vector”.**

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