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Atmospheric and surface parameters retrieved with IR-sounder IRFS-2 data – numerical modeling

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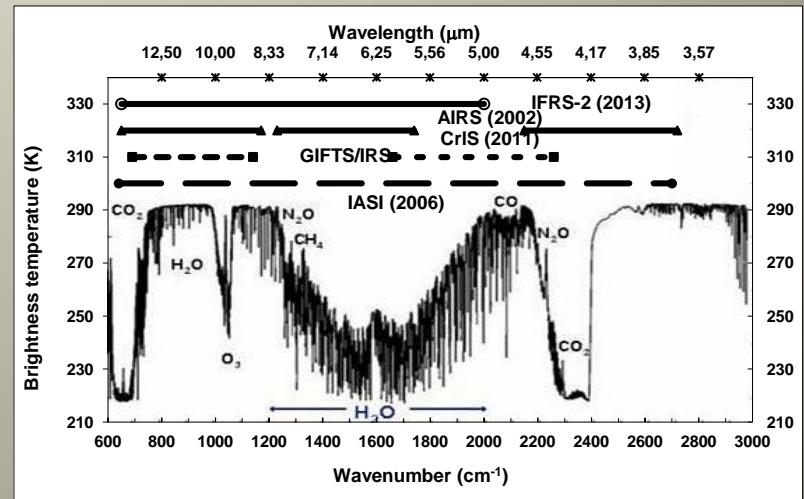
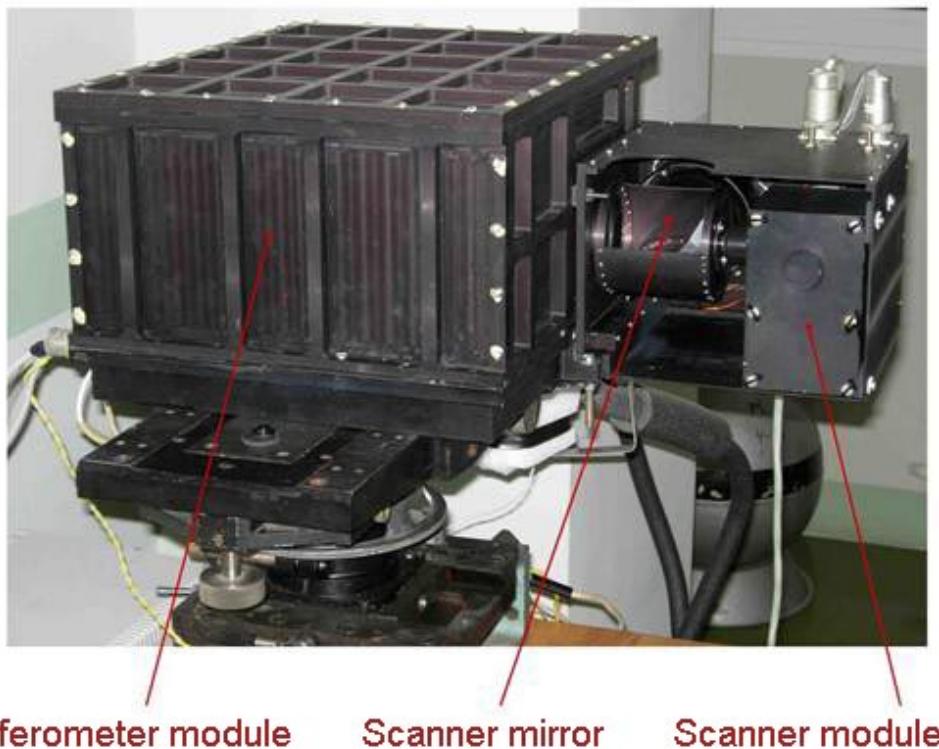
"IASI Infrared Accuracy from Space In a fragile world", Hyères Les Palmiers- France, 4-8 February 2013

OUTLINE

- Short description of IRFS-2 instrument performance
- Ground-based testing of IRFS-2
- IRFS-2 data inversion techniques
- Simulation studies and error statistics analysis
- Further development of IRFS instrument series

Abstract. The short description of a new Russian IR-sounder of high spectral resolution IRFS-2/Meteor-M N2 is given including the analysis of basic characteristics. Measured spectra could be used for the retrieval of atmospheric and surface parameters such as temperature/humidity profiles, surface temperature and emissivity. The experiments have been carried out for simultaneous retrieval the temperature/humidity profiles, surface temperature and spectral emissivity for different land surfaces from synthetic IRFS-2 sounder data. Synthetic spectra were calculated with specially developed Fast Radiative Transfer Model. The inversion procedure for IRFS-2 data consists of two parts: a multiple linear regression estimator for the first guess retrieval (or neural network technique-ANN), and a special procedure for the inverse problem solution itself. A *priori* information on all retrieved parameters together with the PCA techniques are used. Error statistic for the temperature/humidity profiles, surface temperature and emissivity retrievals is presented.

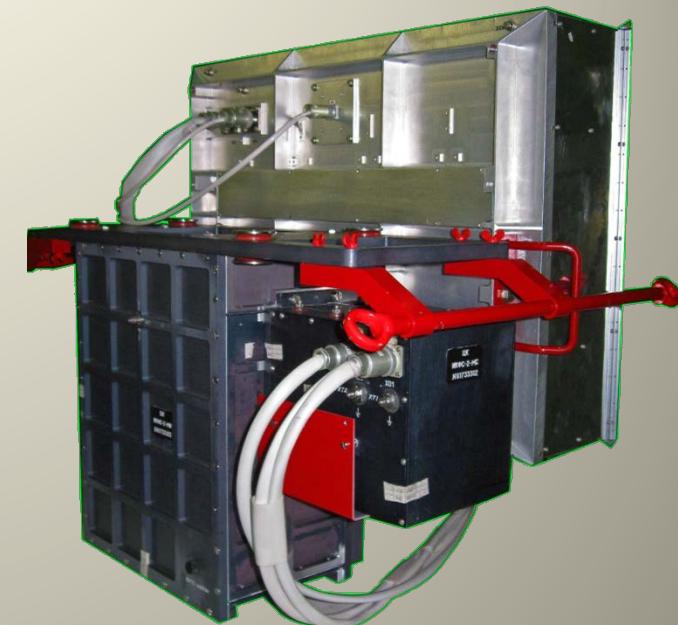
The advanced IR sounder IRFS-2 (InfraRed Fourier Spectrometer-2) designed and manufactured by Keldysh Center (Roskosmos) is planned to be launched aboard “Meteor-M” N 2 satellite (2013). The IRFS-2 instrument assembly includes optical unit, data processing and power supply system and radiative cooler. The optical unit is separated into several modules: interferometric module (IM), pointing module, calibration module. IM includes interferometer of double pendulum type and radiometer. The figure below demonstrates the IRFS-2 instrument sample prepared for testing.



Comparison of various IR sounder spectral ranges, see (Smith et al., 2009)

IRFS-2 Infrared Fourier Transform Spectrometer for Temperature/Humidity Sounding

Satellite	Meteor-M N2, 2013
Spectral range	5-15 μm (667-2000 cm^{-1})
Spectral resolution	0.4 cm^{-1} (without apodization)
Swath width	1000-2500 km
Spatial grid spacing	60-110 km
Spatial resolution	30 km
NESR, $\text{W}/(\text{sr}\cdot\text{m}^2\cdot\text{cm}^{-1})$	$3\cdot10^{-4}$ – 15 μm , $1\cdot10^{-4}$ – 13 μm $3\cdot10^{-4}$ – 6 μm
Radiometric accuracy	0.5 K
Weight	50 kg
Power consumption	50 W
Data flow	600 Kb/s



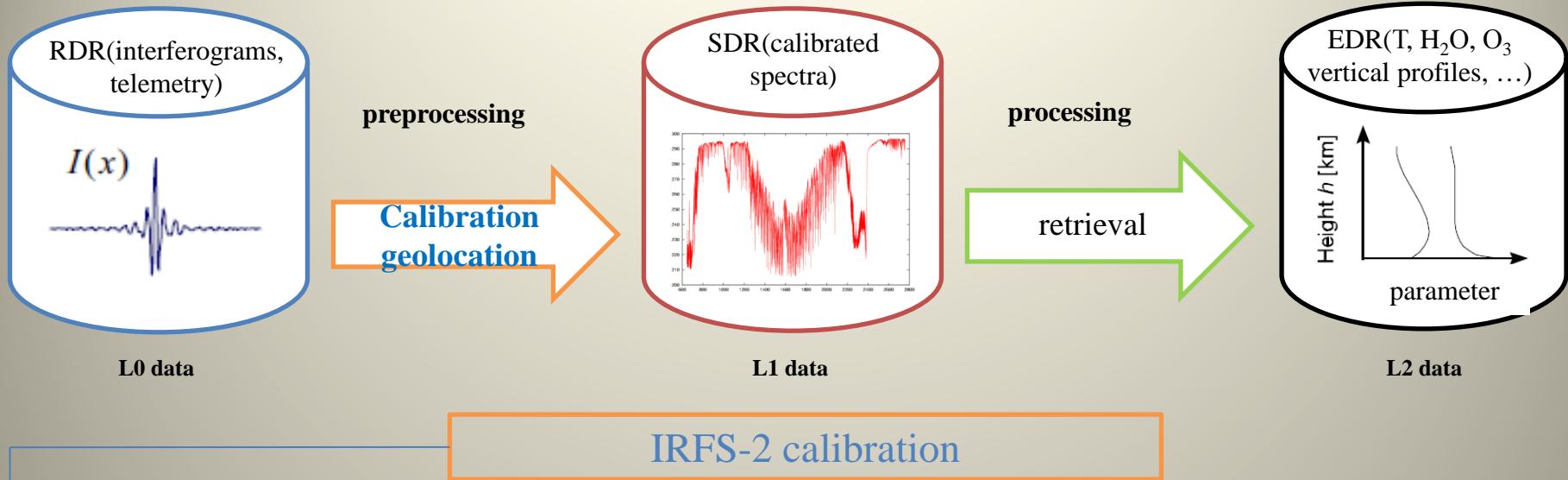
IRFS-2 Calibration	
Radiometric	nonlinearity correction, ICT, NESR/NEdT estimation
Spectral	Instrument Line Shape measurement, metrology laser characterization
Geometric	IFOV shape measurement

IRFS-2 spectral range (5 - 15 μm) covers different regions for various sounding products generation

	Nº	Absorption band	Application
1	665 to 780 cm^{-1}	CO_2	Temperature profile
2	790 to 980 cm^{-1}	Atmospheric window	Surface parameters (T_s , ε_v), Cloud properties
3	1000 to 1070 cm^{-1}	O_3	Ozone sounding
4	1080 to 1150 cm^{-1}	Atmospheric window	T_s , ε_v , Cloud properties
5	1210 to 1650 cm^{-1}	H_2O , N_2O , CH_4	Moisture profile, CH_4 , N_2O column amounts

Ground-based testing of IRFS-2

IRFS-2 data processing chain



IRFS-2 calibration

radiometric:

- 1) spectral sensitivity and intrinsic emission derivation
- 2) phase distortion correction
- 3) sensor nonlinearity correction
- 4) onboard black body spectral emission measurements
- 5) threshold NESR(v) estimation

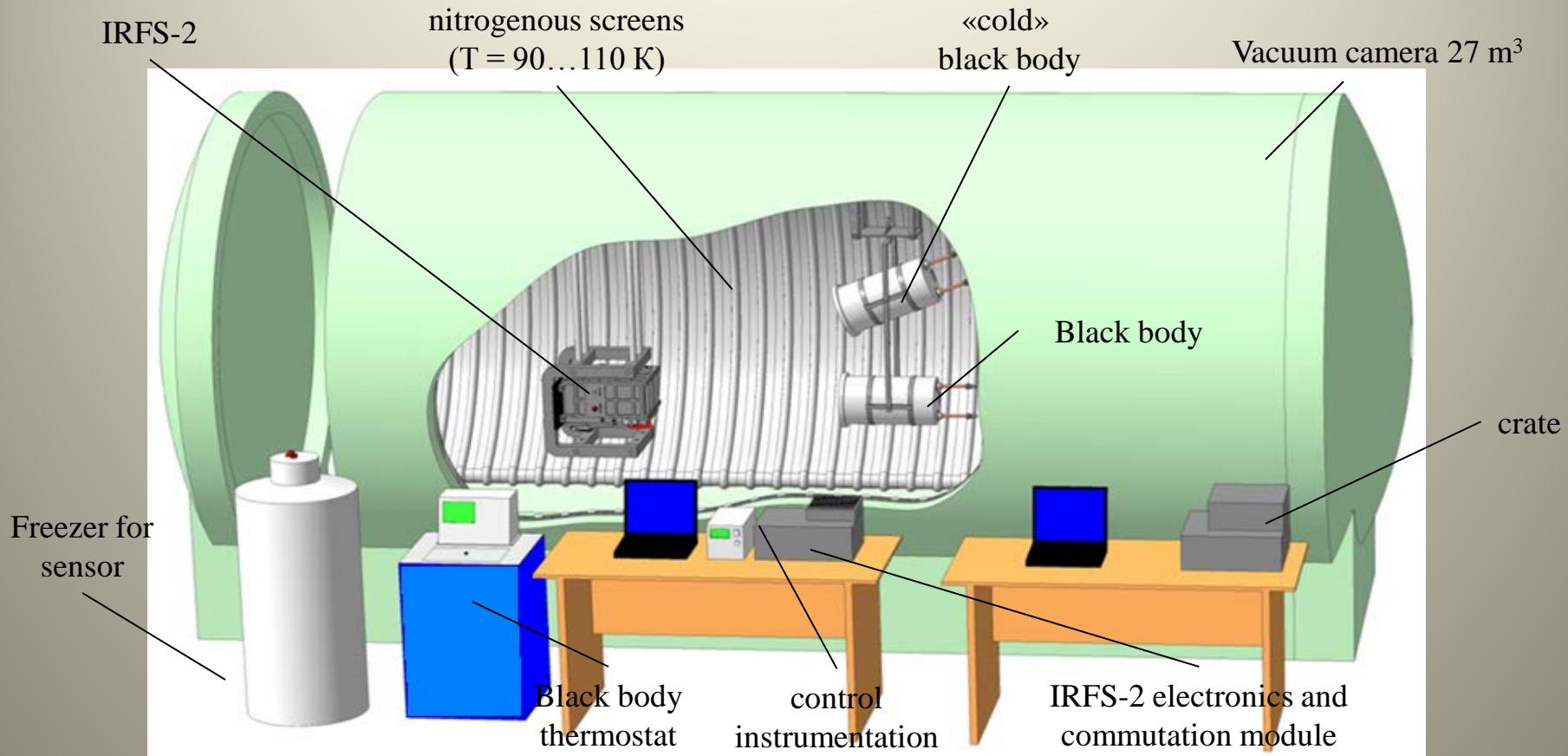
spectral:

- 1) wave number scale matching
- 2) instrument spectral response function characterization

geometric

- 1) IFOV shape measurement
- 2) geolocation

IRFS-2 radiometric calibration

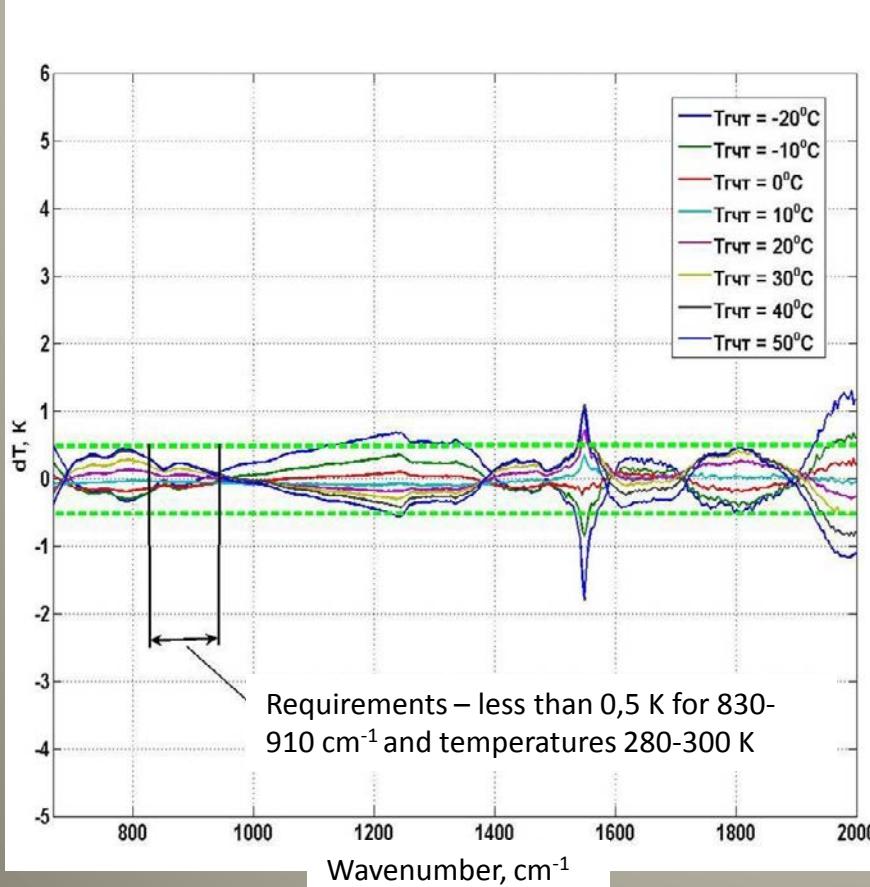


Measurements taken:

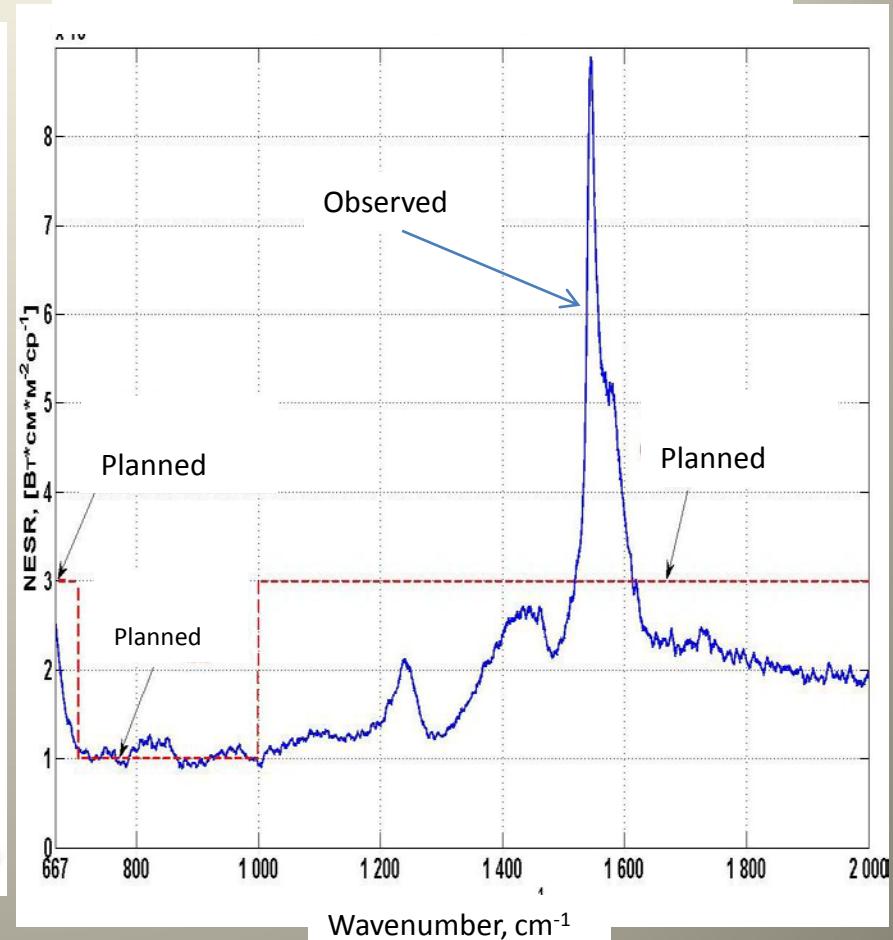
- Sensor temperatures: 15, 20, 23°C;
- Black body temperatures: -20,-10,10,20,30,40,50°C;
- For each cycle: interferogram measurement for black body and “cold” black body.

IRFS radiometric calibration results

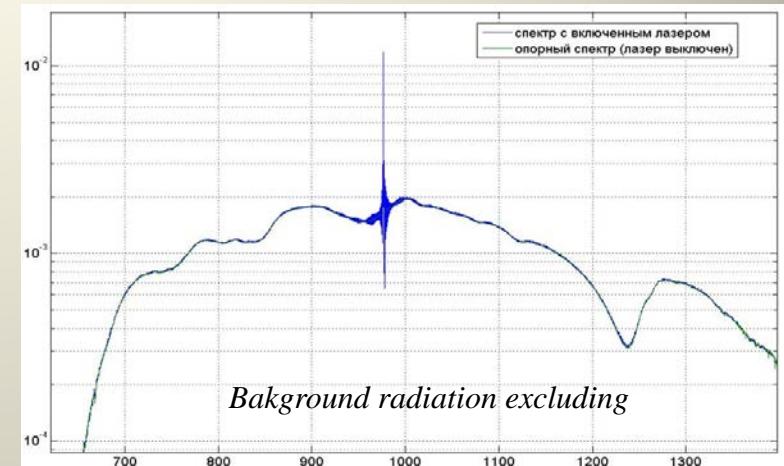
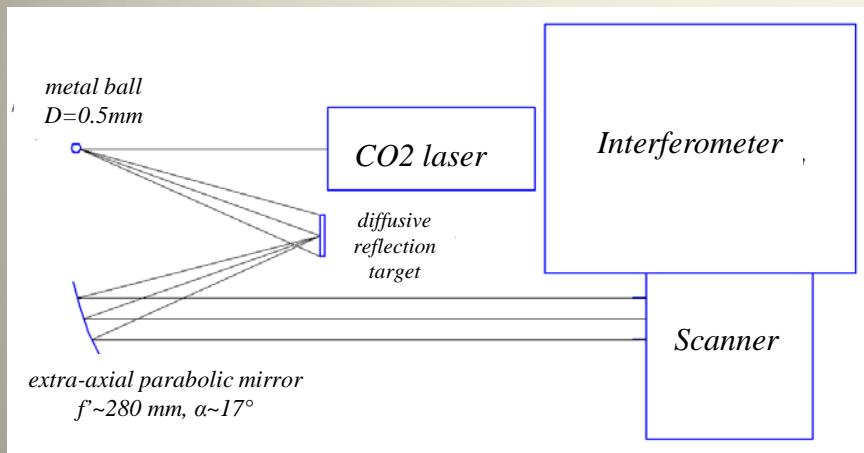
Accuracy of spectral radiance measurements



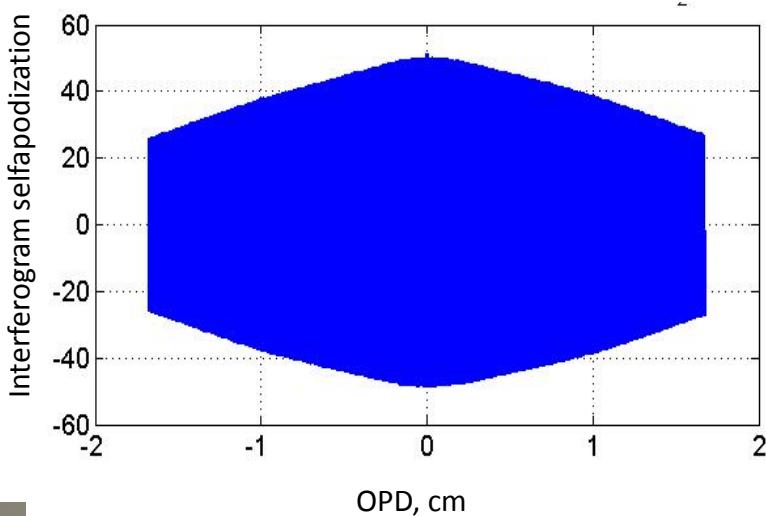
Behavior of threshold NESR



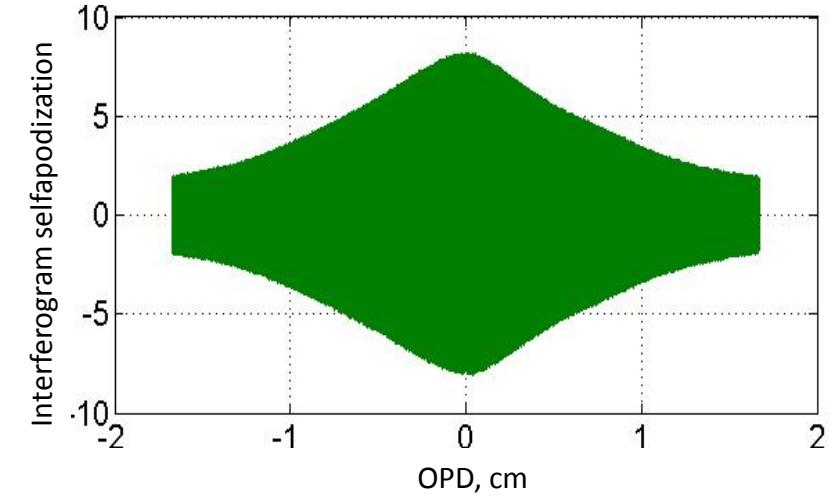
IRFS-2 spectral calibration – ISRF measurement



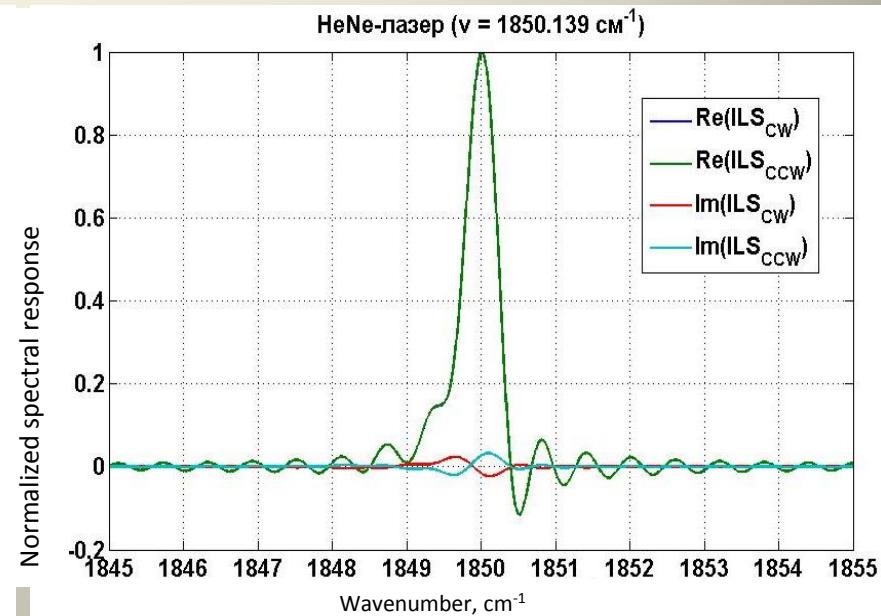
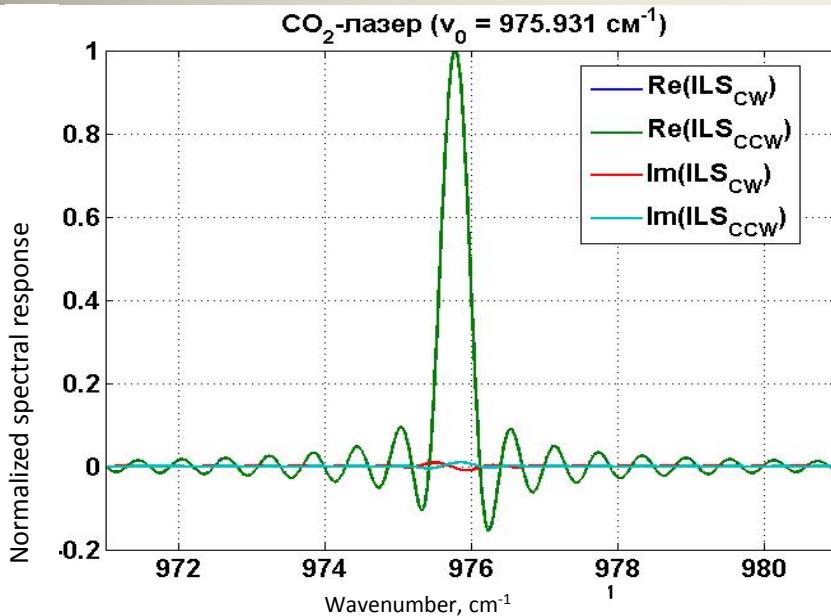
Interferogram for monochromatic radiance (CO_2 -laser)



Interferogram for monochromatic radiance (HeNe -laser)

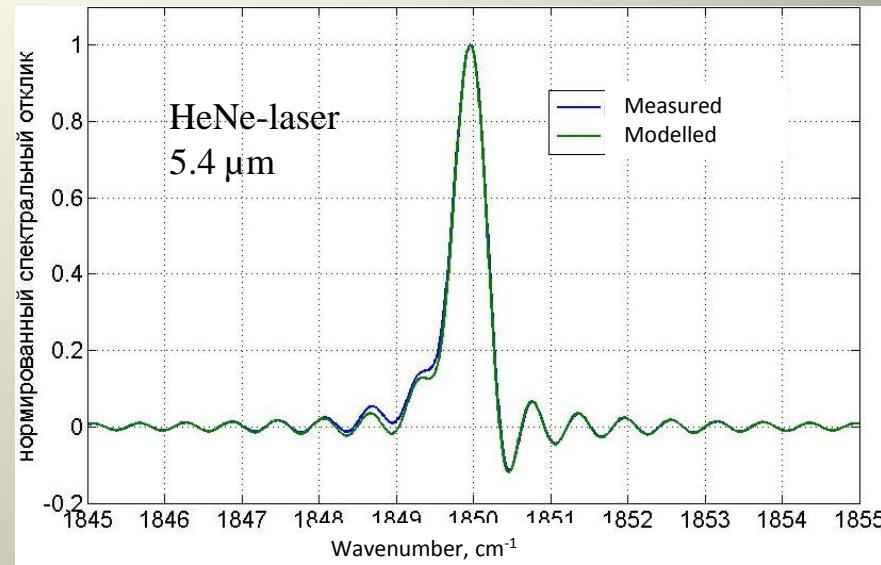
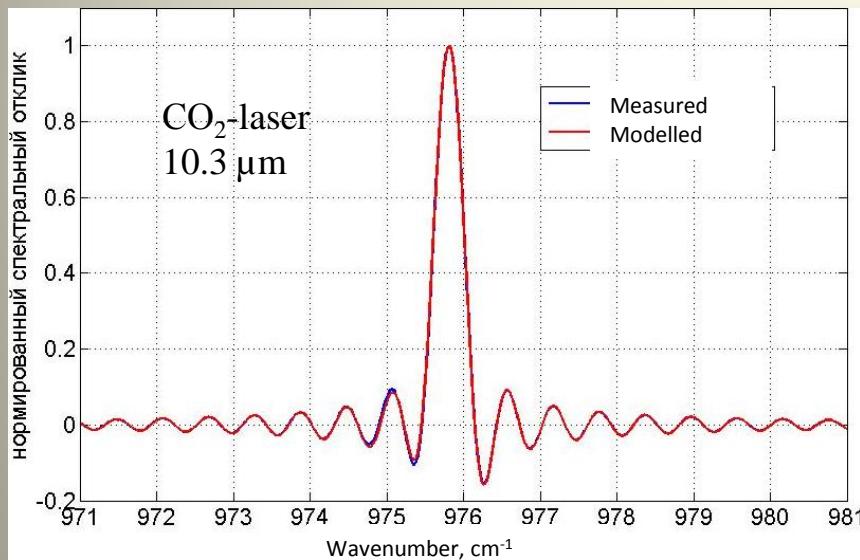


IRFS-2 spectral calibration results

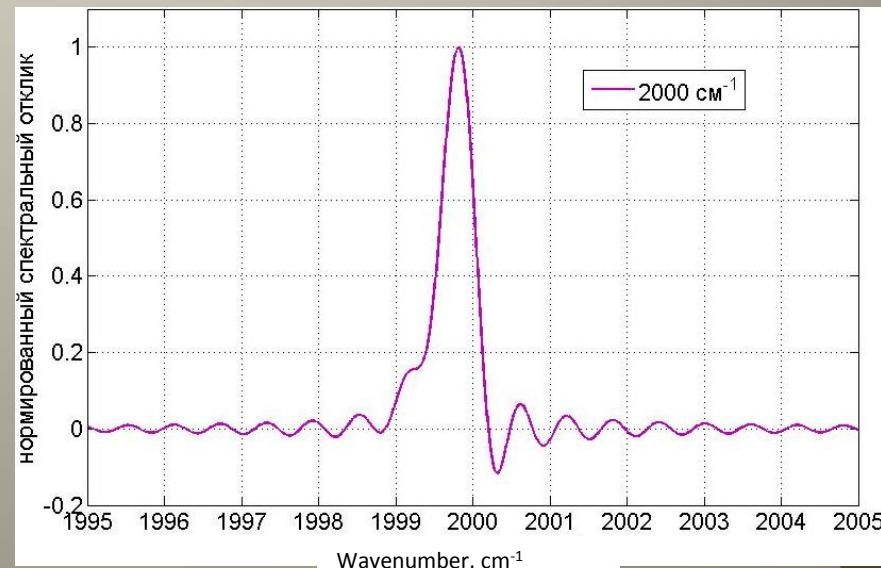
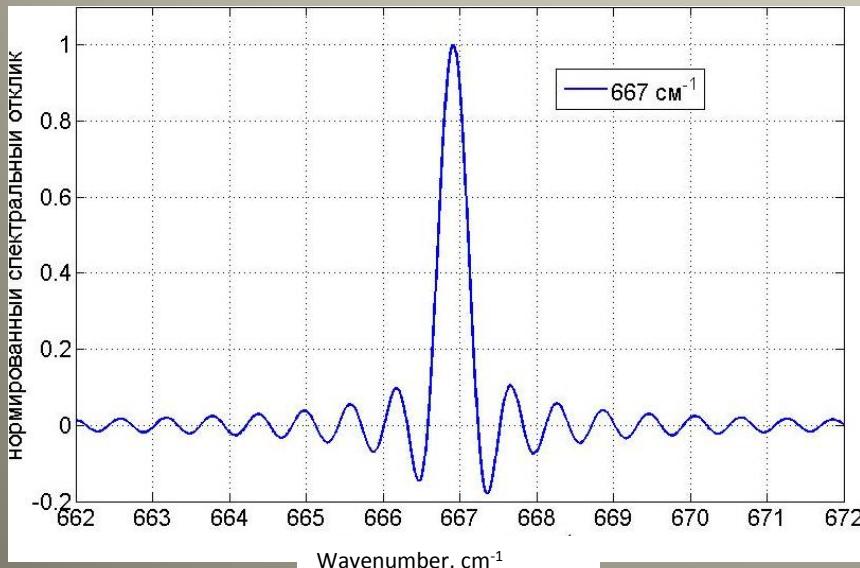


- spectral response function width at 0.5:
0.39 cm^{-1} for CO₂ – laser ($\sim 10.3 \mu\text{m}$)
0.47 cm^{-1} for HeNe – laser ($\sim 5.4 \mu\text{m}$)
- maximum line shift to the left at a wave number scale:
0.119 cm^{-1} for CO₂ – laser line
0.184 cm^{-1} for HeNe – laser line
- spectral response function is asymmetric with respect to the maximum
- spectral response has minor imaginary component

IRFS-2 modeled and measured ISRF



Modeled spectral response functions for 667 cm^{-1} and 2000 cm^{-1}



IRFS-2 geometric calibration – IFOV shape measurement

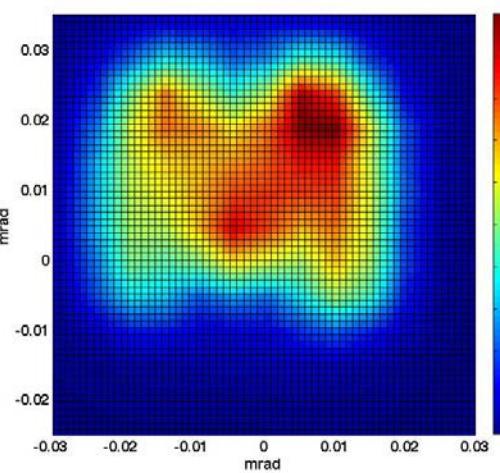
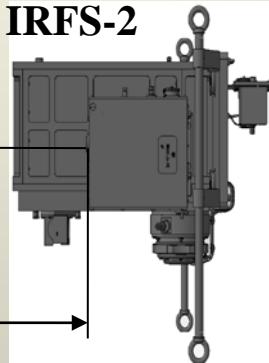
Black body



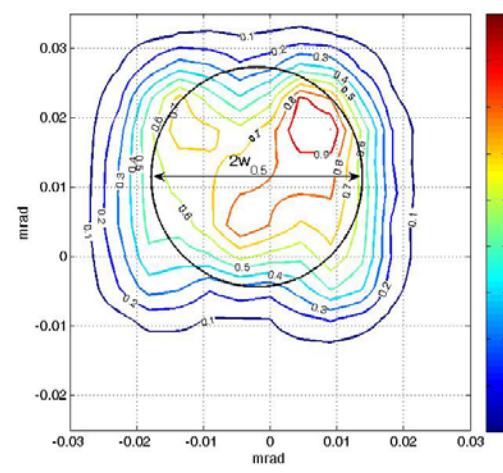
$T = 800^\circ\text{C}$

$L = 10 \dots 15 \text{ m}$

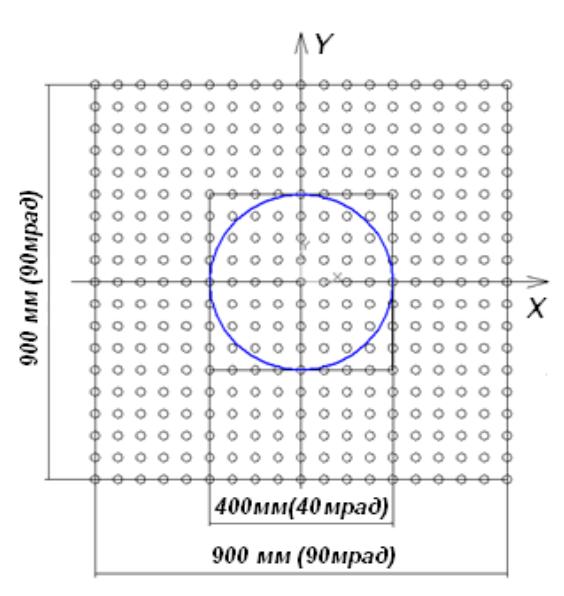
IRFS-2



Instrument sensitivity distribution within IFOV



Energy distribution within IFOV



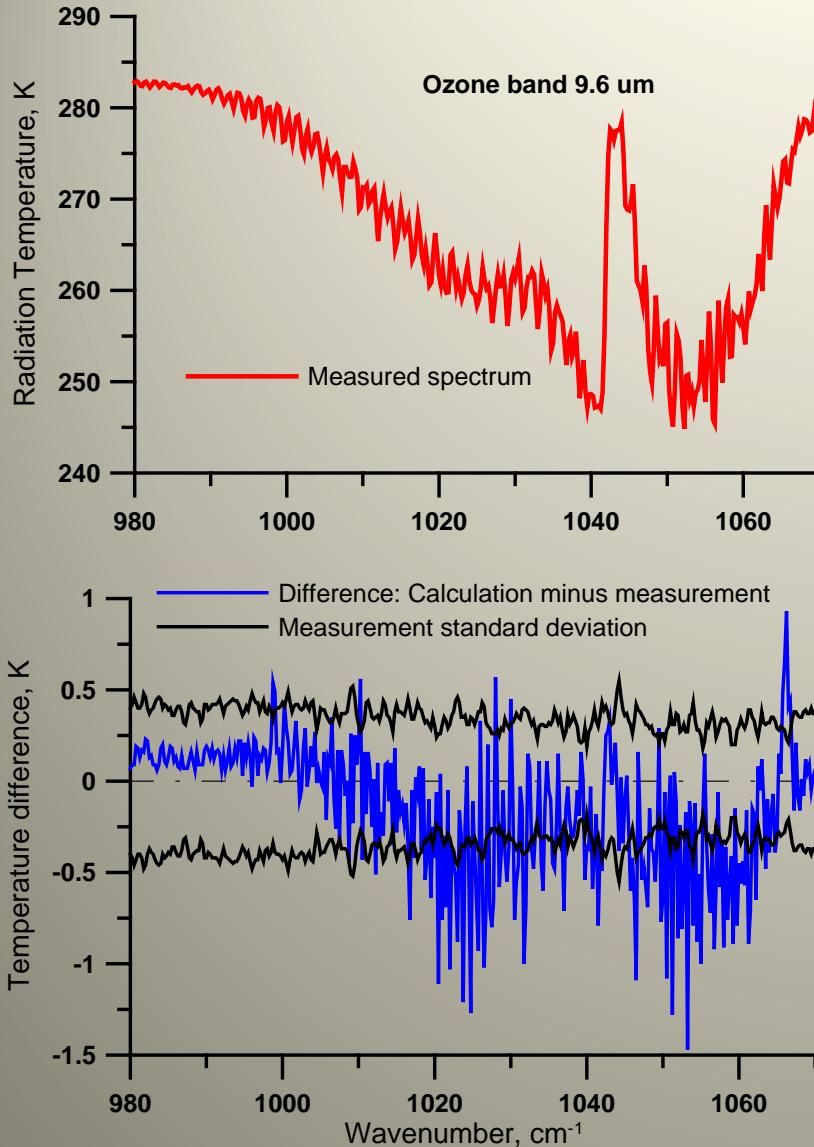
*IFOV measurement grid:
Grid size– 50 mm (5 mrad)*

Energy level	95 %	80 %	70 %	50 %
IFOV	57 mrad	44 mrad	39 mrad	31 mrad

Retrieval methodology

- The unknown state vector ϕ includes as components temperature (T), humidity (q) and ozone concentration profiles (vectors) together with methane/nitrous oxide columns as well as land surface temperature and spectral emissivity parameters. The last ones are principal component (PC) scores in the EOF decomposition of surface spectral emissivity (SSE) function.
- Clear-sky radiances (brightness temperatures) measured in all IRFS-2 channels (full spectra) are used for the state vector ϕ retrieval.
- The IRFS-2 data inversion scheme consists of two steps:
 - use of multiple linear regression (MLR) for generation of the first guess retrieval, moreover all components of sought vector ϕ are retrieved in parallel utilizing full spectrum data;
 - (or use of combined EOF/Neural Network technique-ANN to retrieve temperature/humidity profiles);
 - use of physical inversion procedure based on modified Gauss-Newton iteration algorithm; the procedure is applied to IRFS-2 data in the subset of pre-selected (dedicated) channels, moreover the channel selection is based on the Jacobians and information content analysis.

IR Radiance transfer model (SPbSU, based on LBL calculations)



Comparison of measured by IASI and calculated spectra, cloudless atmosphere.

It is seen that, in most cases, differences between experimental and calculation values (in terms of “brightness temperature”) is not more than 1 K, that shows relatively high quality of developed radiation model.

FRTM(IRFS-2) based on RTTOV-9

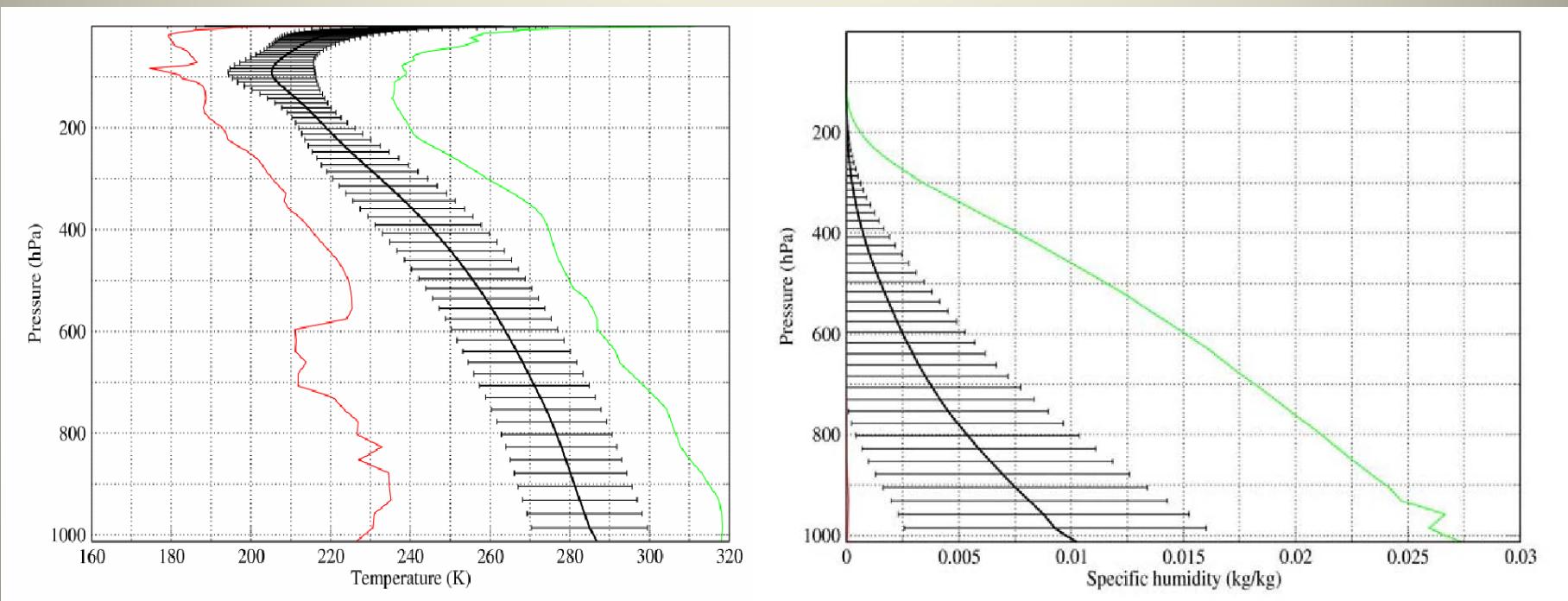
This FRTM should provide fast and accurate modeling of measured spectra with errors less or equal to the instrumental noise. Also, this FRTM should be used to calculate various parameters like optical depth, transmittances, Jacobians etc.

RTTOV - 9 and RTIASI-4 were used as a basis for our FRTM development. With line-by-line (LBL) calculations (LBLRTM 11.7, January 2010) an ensemble of synthetic spectra to be measured by IRFS-2 has been generated for the representative sample of diverse atmospheric models (profile training set of Matricardi et al.). Trace gases CO₂, N₂O, CO and CH₄ were used as profile variables.

The developed FRTM is a set of regressions for each IRFS-2 channel. The regressions were obtained using calculated spectra and a set of atmospheric profile dependent predictors similar to those of RTTOV-9. Special procedure to account for scattering properties of clouds or dust layers has been developed.

Verification was performed in two stages through comparison of FRTM- and LBLRTM- calculated spectra. Firstly, the comparison was performed for IASI channels using existing RTTOV (RTIASI) models. Then, the comparison has been performed for IRFS-2 channels. It was shown that the RMS difference is less than 0.5K in the spectral range 660-1300 cm⁻¹. This value is what a typical instrumental noise of IRFS-2 should be.

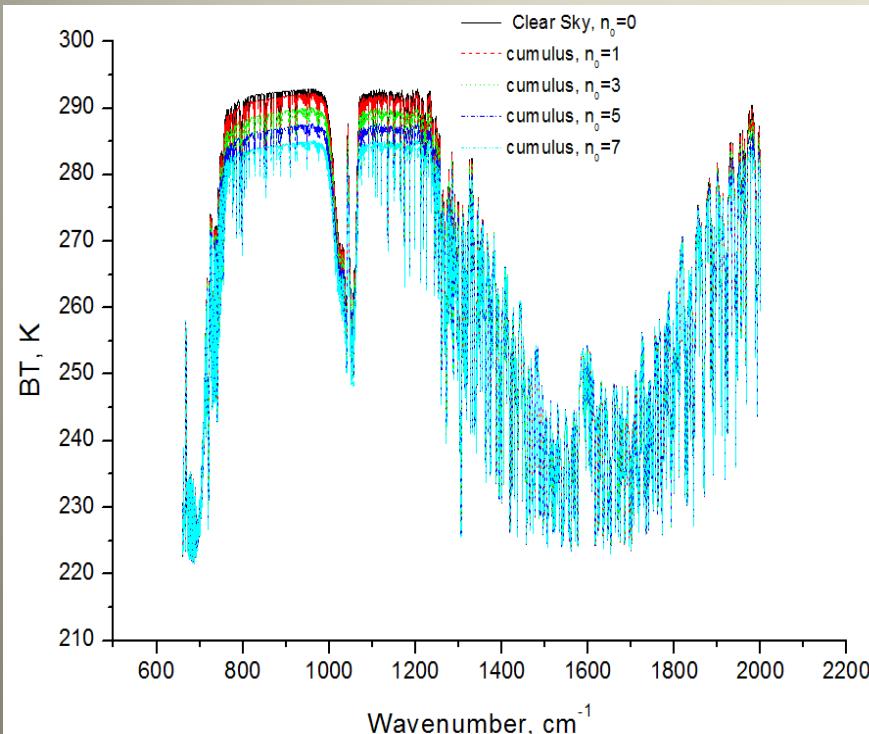
Statistics of temperature and humidity profiles



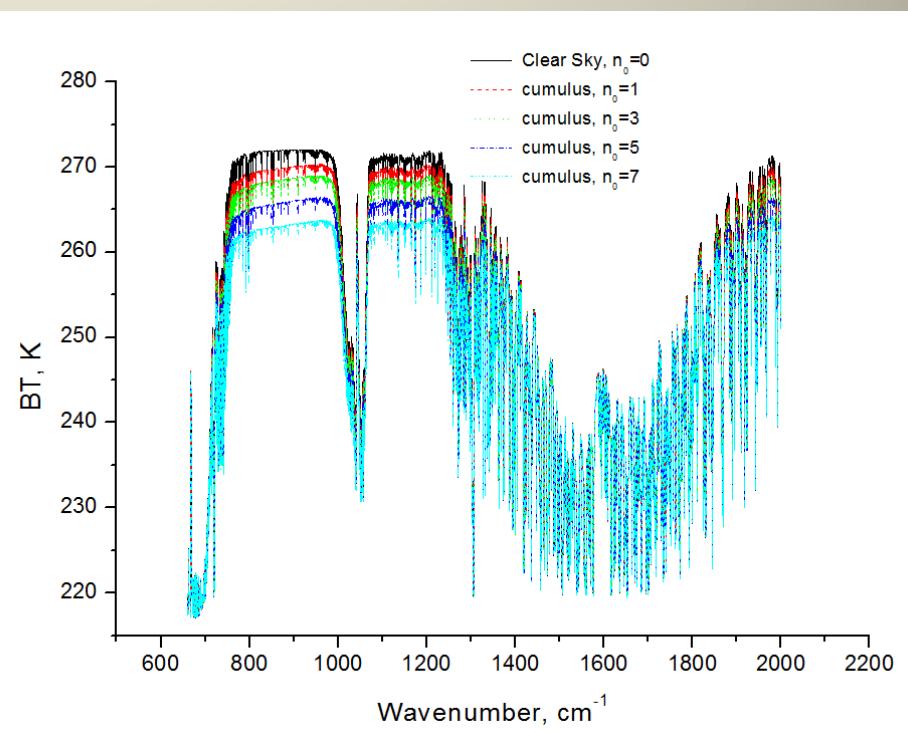
Matricardi et al. : The generation of RTTOV regression coefficients for IASI and AIRS using a new profile training set and a new line-by-line database, ECMWF Research Dept. Tech. Memo. 564, 2008, available at:
<http://www.ecmwf.int/publications>

Calculated spectra of IR outgoing radiation for various atmospheric models

Summer

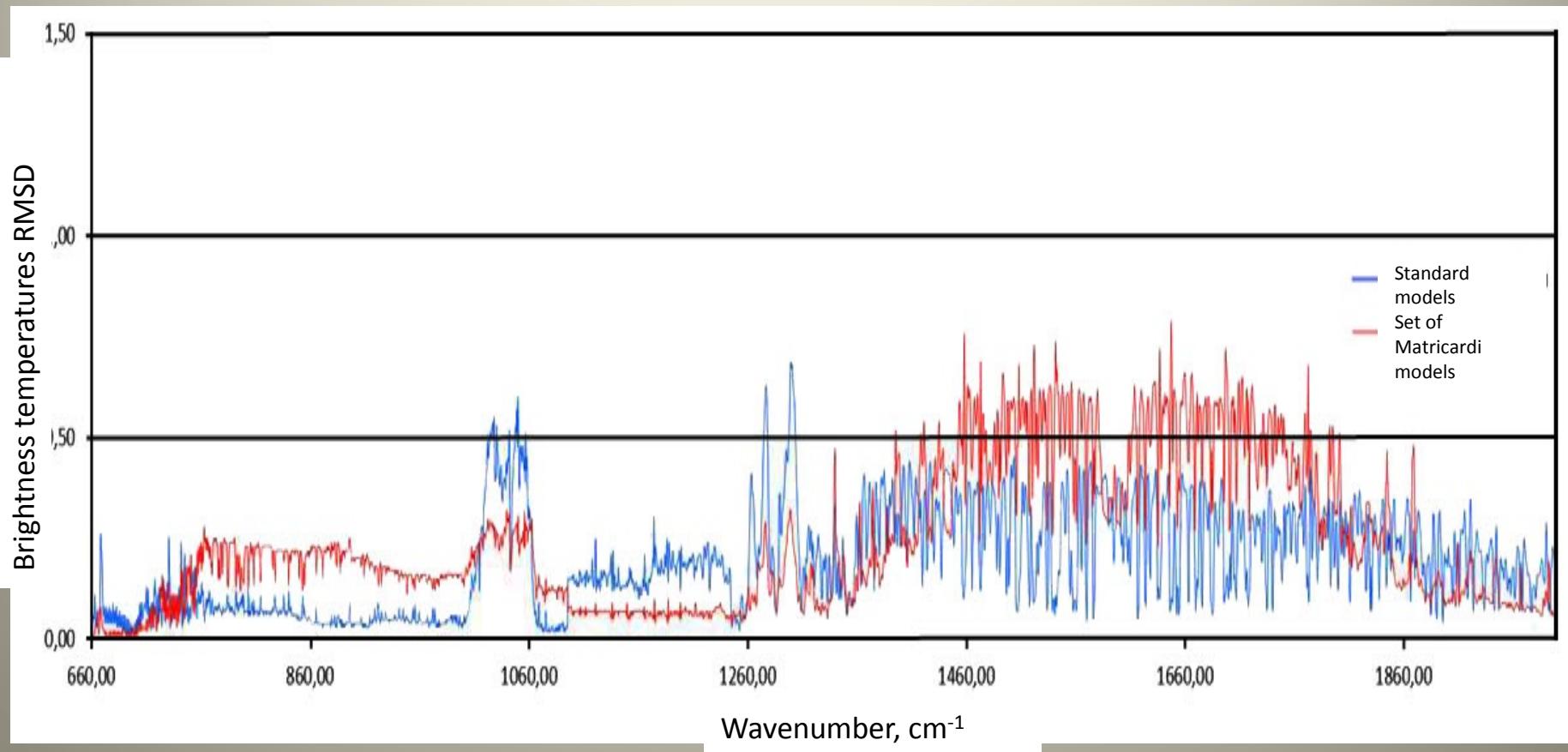


Winter



Monte Carlo-based radiative transfer model was used to verify LBL RTM calculations

FRTM(IRFS-2) modeled spectra vs LBLRTM for various atmospheric models



Calculation time for one IRFS-2 spectra is about 0,5 s

Simulation studies

The global **database** of state vectors (atmospheric profiles and surface emissivity and temperature) has been compiled for the numerical modeling of IRFS-2 data “inversion”.

It comprises of:

- database with parameters of cloudiness atmosphere;
- database TIGR with results of aerological and ozone sounding;
- numerical statistical modeling data.

The **database** is a set of 2311 atmospheric temperature, humidity, ozone, methane, nitrous oxide, cloud water profiles together with surface temperature and emissivity (IR spectral range), sea level wind speed and water salinity.

The database allows to simulate IR and MW measurements over land and sea. Data is classified by the seasons and latitude zones.

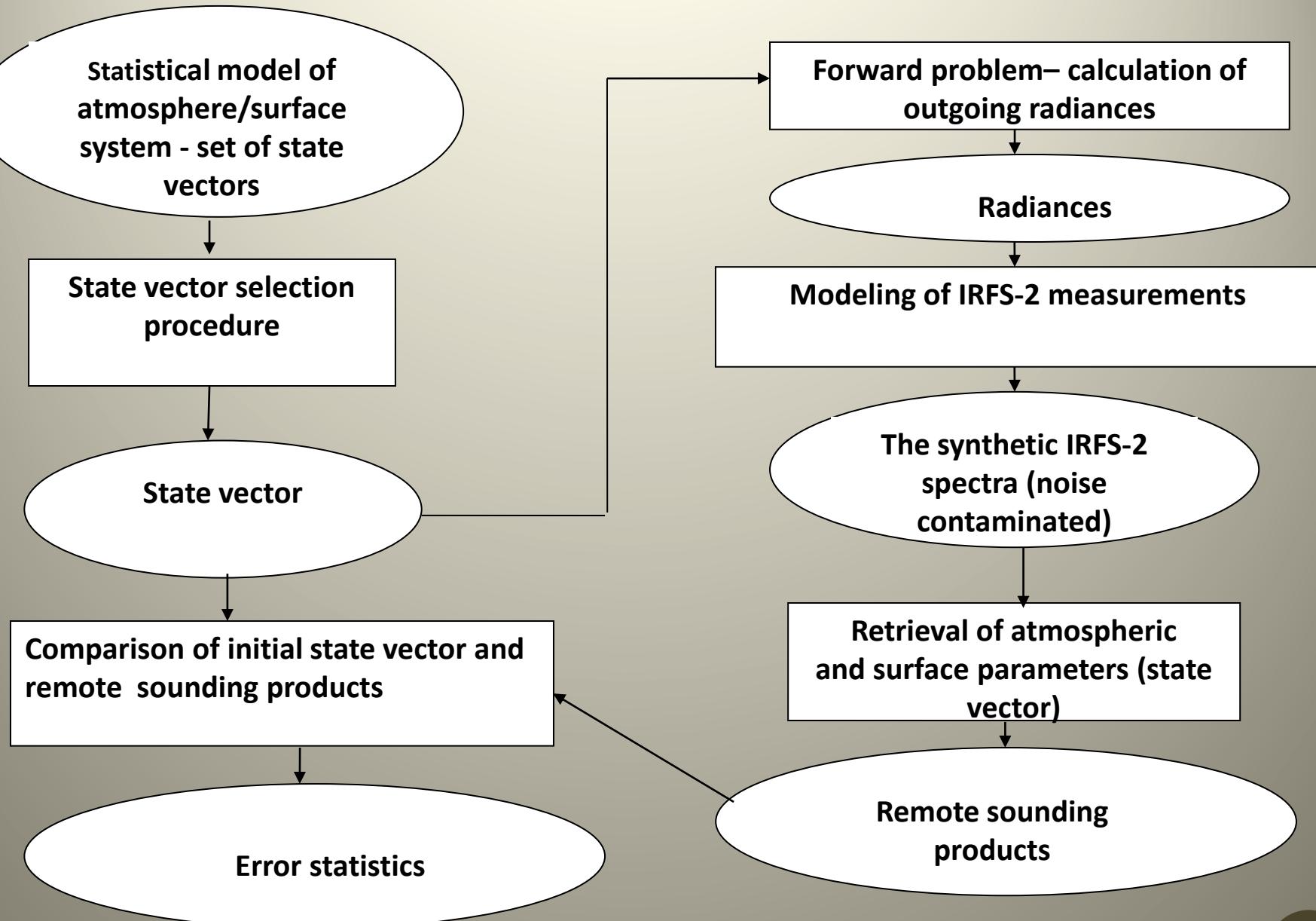
The temperature and humidity profiles approximation using PCA technique

	decomposition error		
	Temperature, K		Humidity. % of RH
Number of vectors	Altitudes 0-40, 57 levels	Altitudes 0-80, 85 levels	
1	8.82	9.37	19.3
2	5.80	7.38	14.3
3	3.61	5.65	11.3
4	2.84	3.57	9.3
5	2.21	2.60	7.9
6	1.76	2.06	6.9
7	1.44	1.68	5.9
8	1.19	1.37	5.2
9	1.01	1.16	4.5
10	0.87	0.97	3.9
11	0.74	0.85	3.5
12	0.64	0.74	3.1
13	0.56	0.64	2.8
14	0.49	0.57	2.5
15	0.43	0.51	2.2
16	0.38	0.45	2.0
17	0.34	0.40	1.8
18	0.29	0.35	1.6
19	0.26	0.31	1.5
20	0.23	0.28	1.3

We need 15 principal components to approximate temperature profile in the 0-40 km layer with accuracy better than 1 K (17 for the layer 0-80 km).

We need 9-10 principal components to approximate humidity profile in the troposphere with accuracy better than 10%.

Numerical modeling of IRFS-2 data “inversion “



Neural network technique (ANN – artificial neural network)

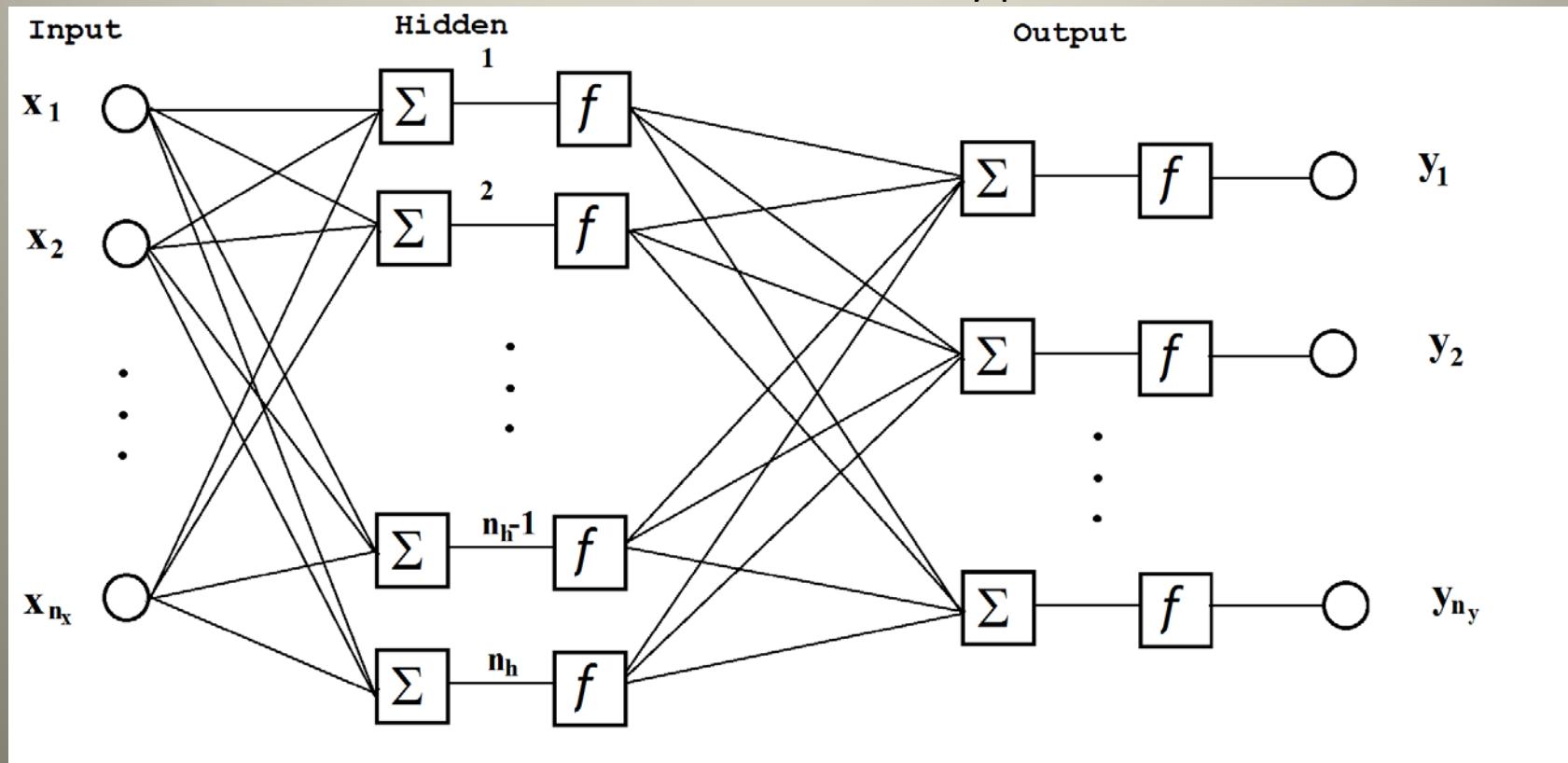
Three-layer perceptron

Input data:

- 1) Principal components of IRFS spectrum
- 2) MTVZA spectrum of Brightness Temperatures

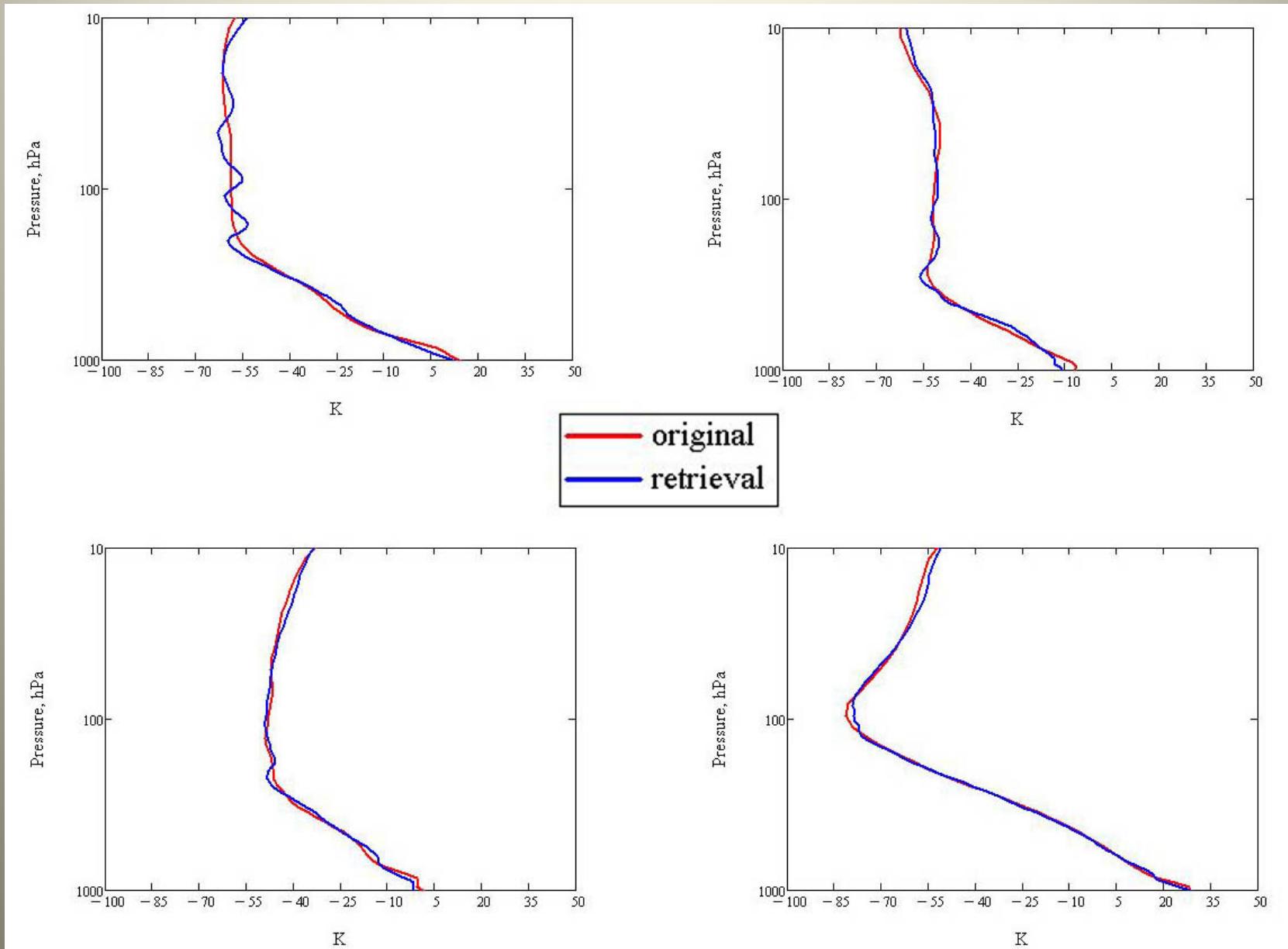
Output data:

- 1) Scalar parameters (surface temperature, total gases amount, water total content etc.)
- 2) Principal components of temperature or humidity profiles



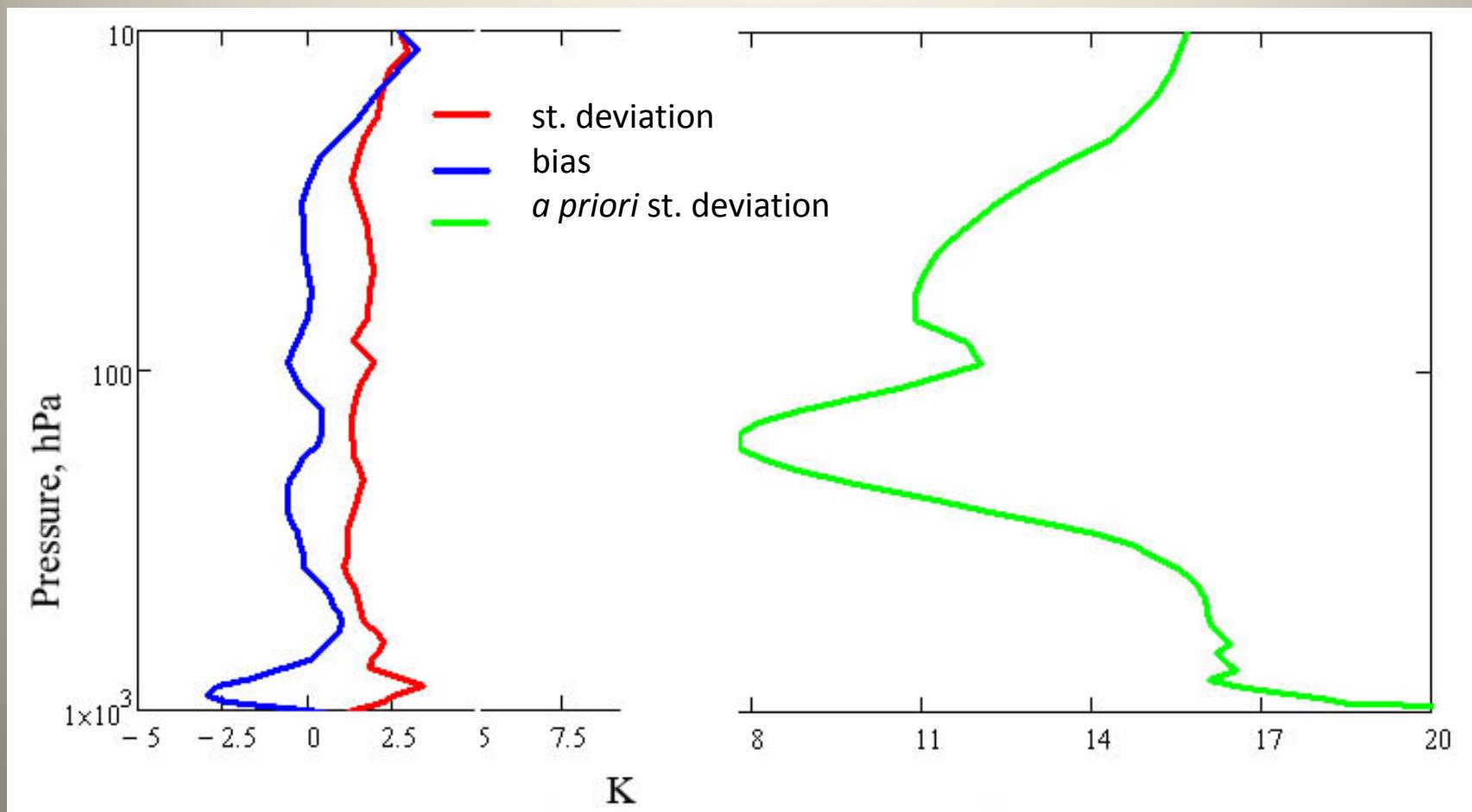
Comparison of T-profile retrievals with original T-profiles

Training – TIGR data set, retrieved – set of Matricardi profiles



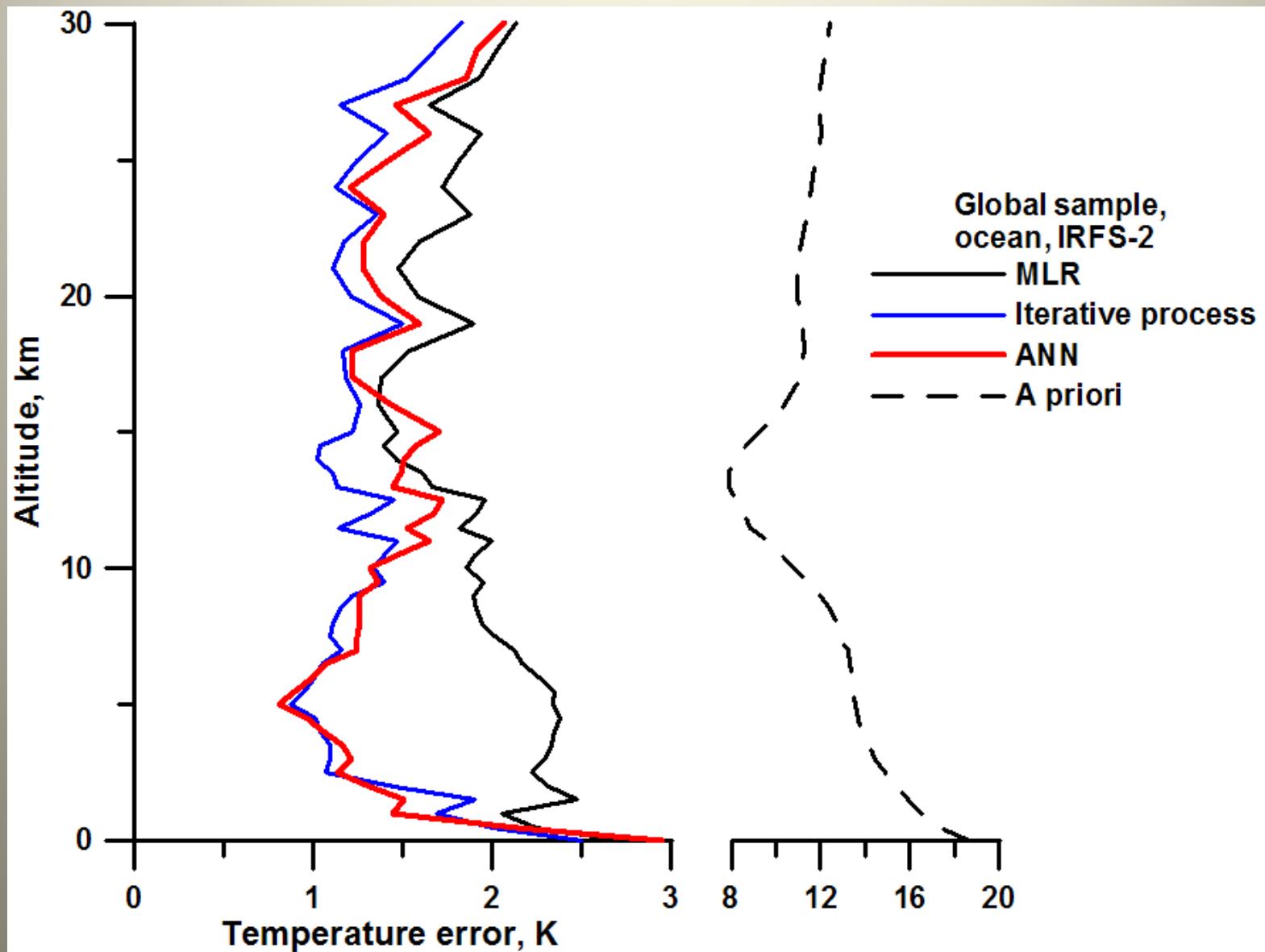
Temperature profile retrieval error statistics

Training – TIGR data set, retrieved – set of Matricardi profiles



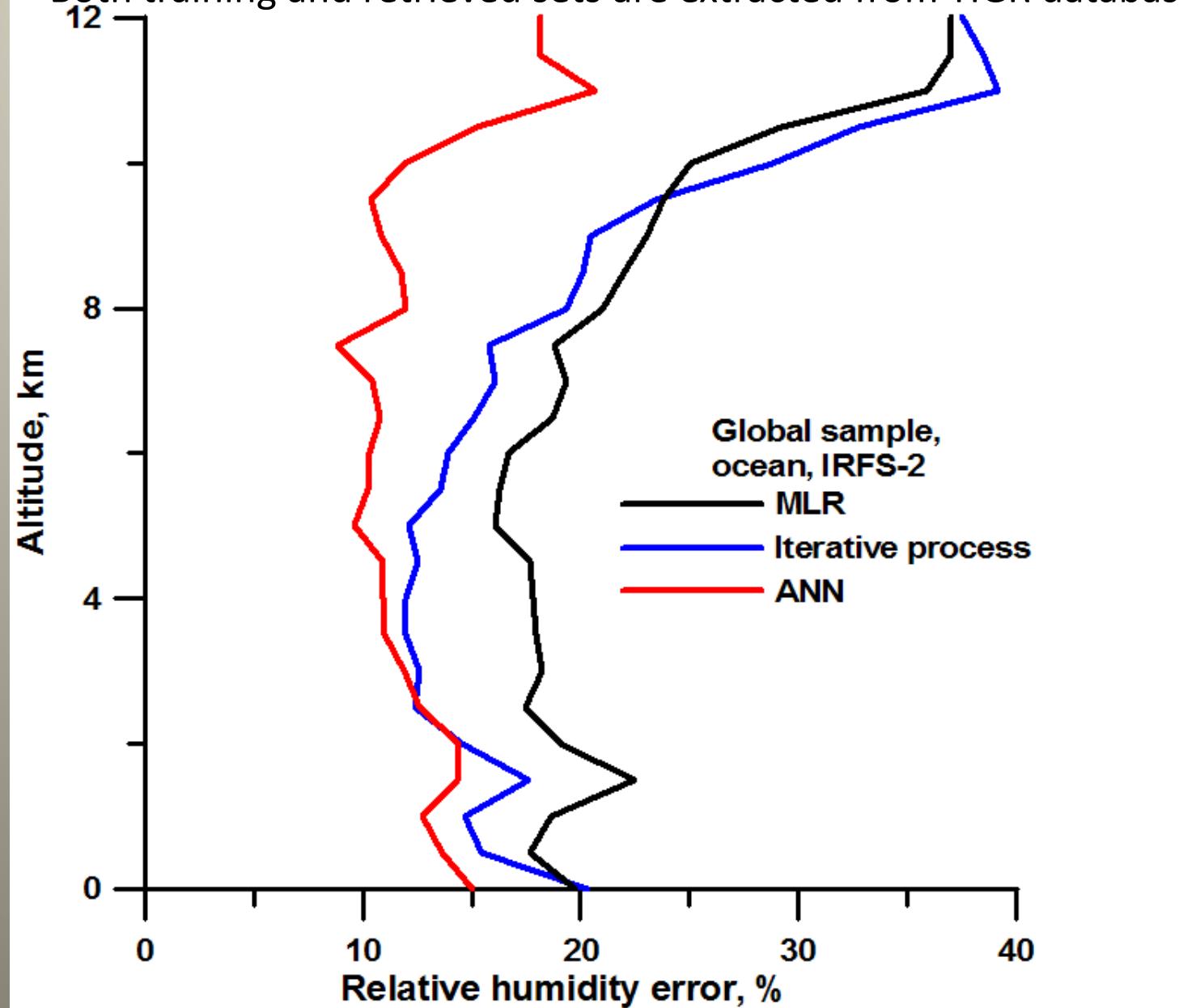
Temperature profile retrieval error statistics

Both training and retrieved sets are extracted from TIGR database



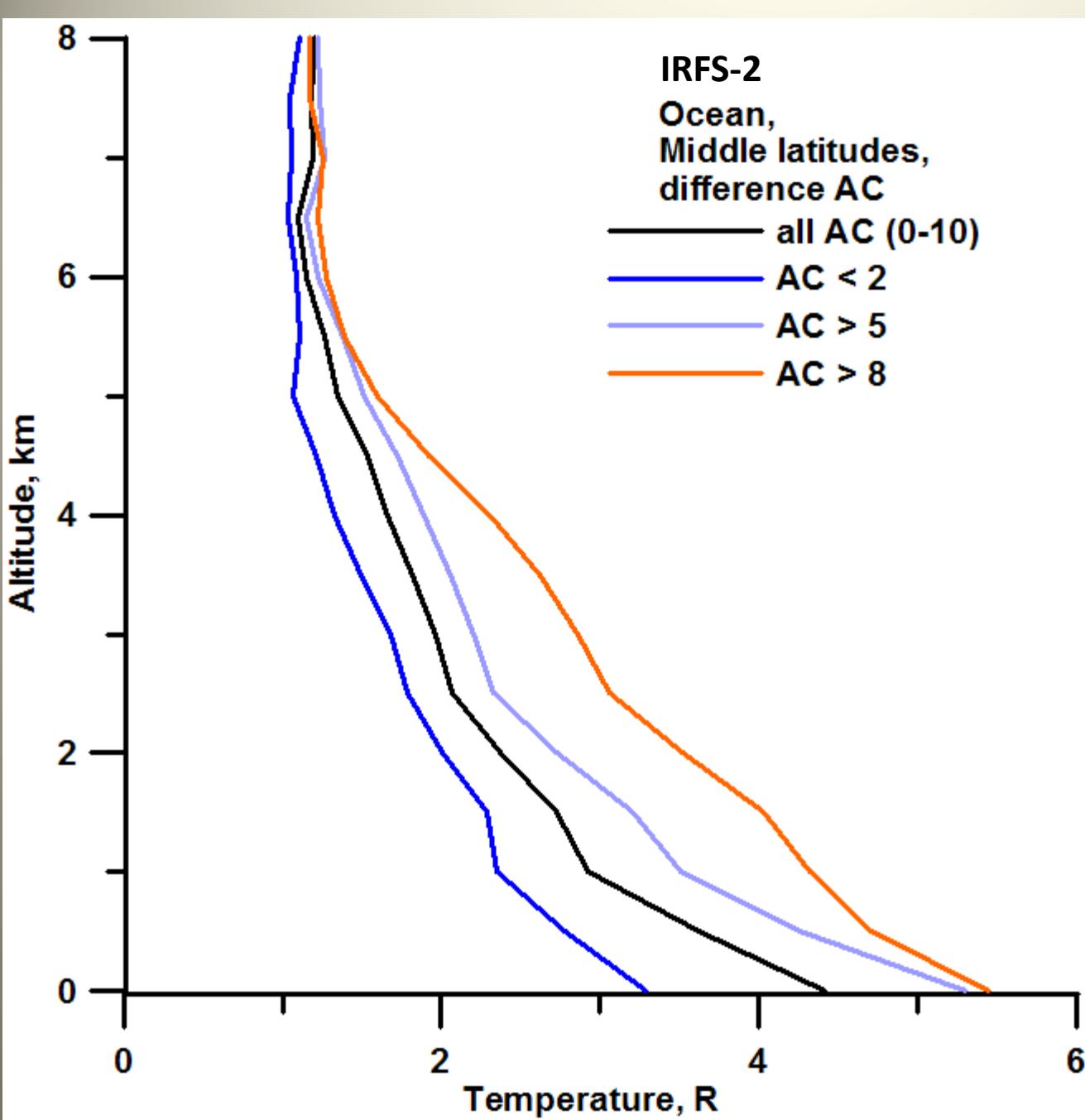
Relative humidity (q) profile retrieval error statistics

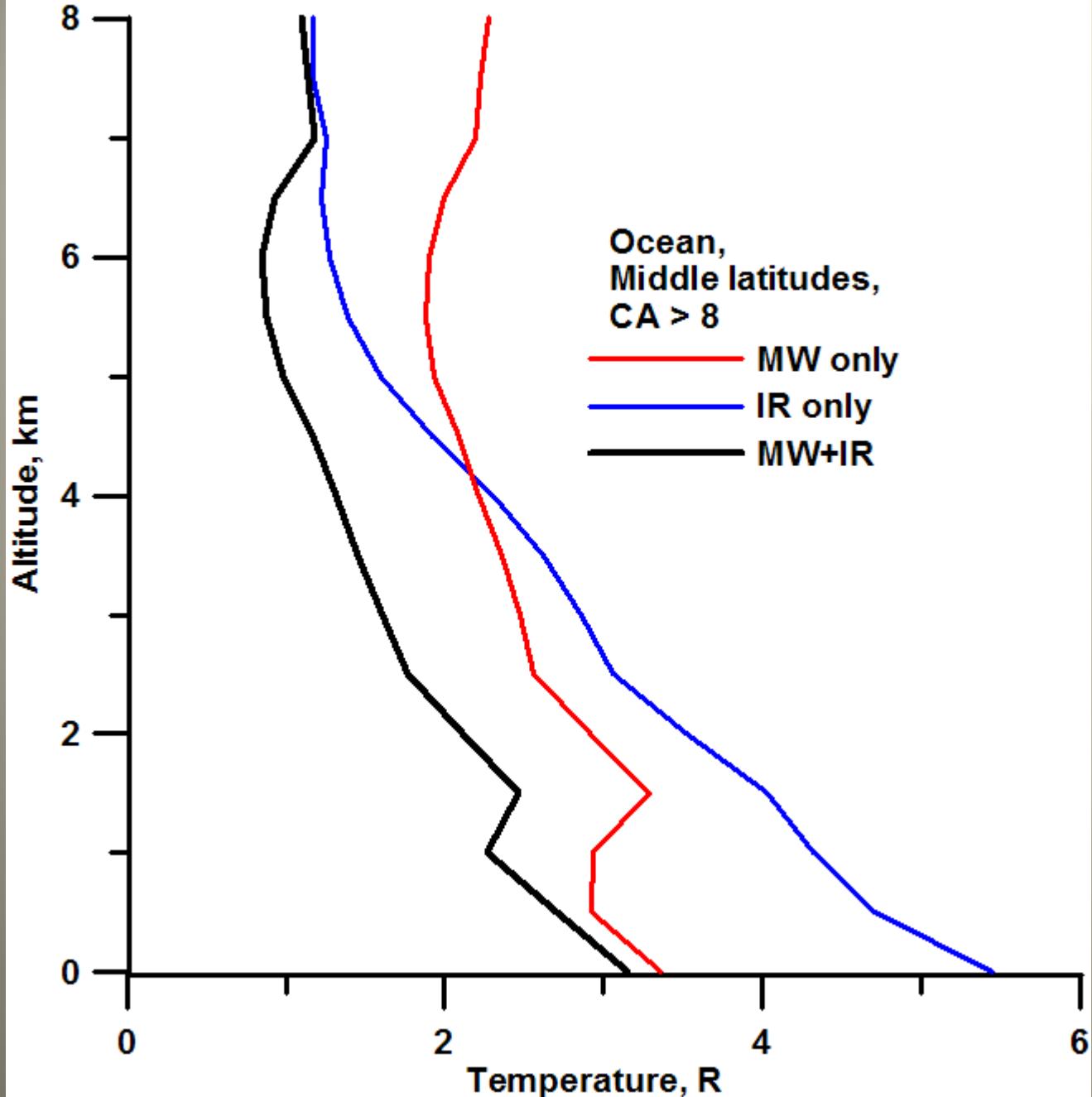
Both training and retrieved sets are extracted from TIGR database



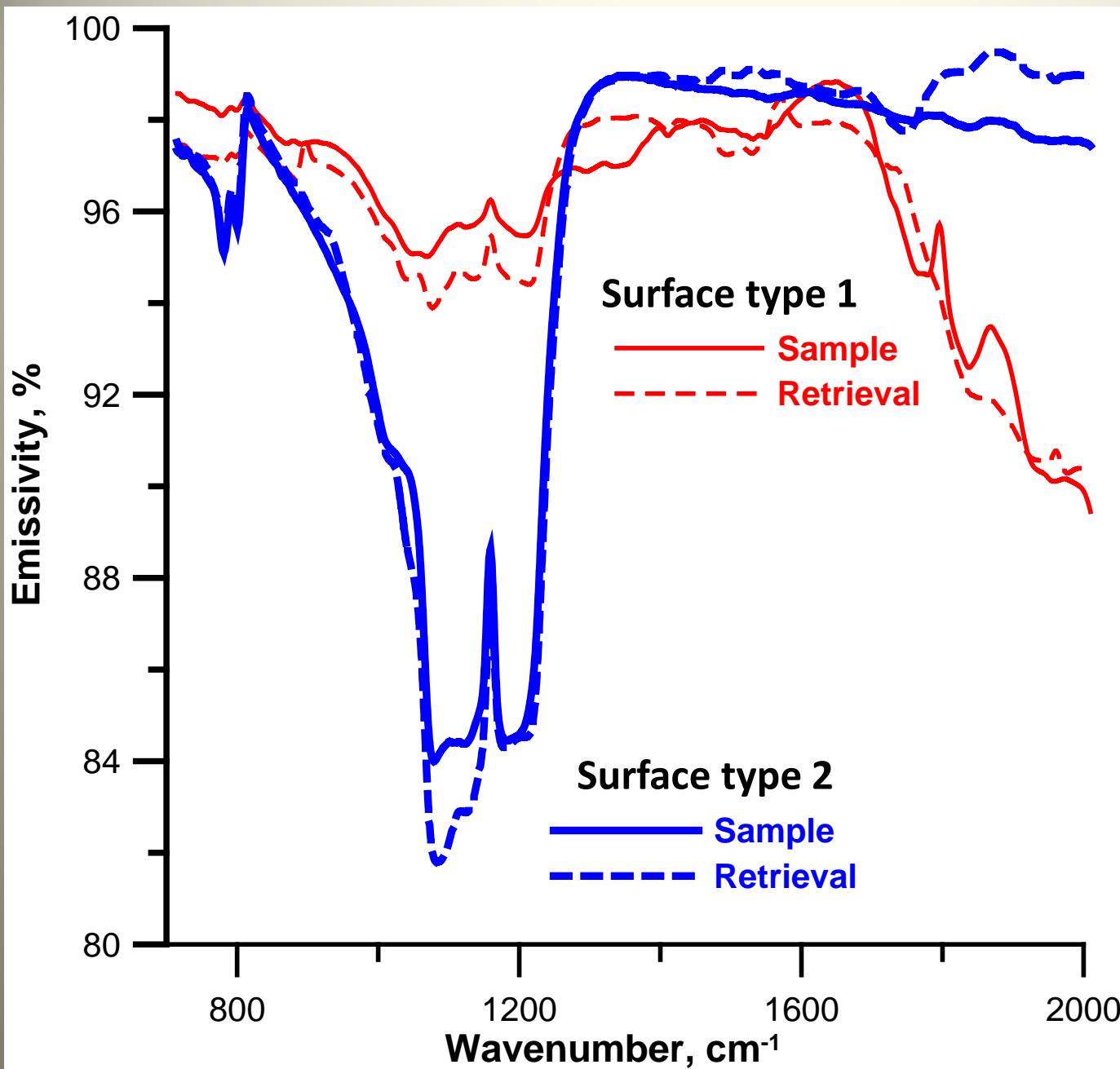
Errors of retrieval the temperature profile (MLR).

IR spectra only,
3 samplings with
different
cloud amounts
(CA)





Errors of retrieval the
temperature profile
from
- MW,
- IR
- MW+IR composition
measurements.
Middle latitudes.
Cloudy atmosphere,
CA > 8.



Two examples of
surface emissivity
retrieval

RMS errors and a priori uncertainty of LST (K) with different resolving operators

Latitudes	Global resolving operator		Local resolving operator		A priori
	Planned noise	Possible noise	Planned noise	Possible noise	
All	0.56	0.64	–	–	18.9
Tropics	0.63	0.71	0.54	0.63	8.6
Mid. latitudes 1	0.51	0.59	0.37	0.45	10.0
Mid. latitudes 2	0.48	0.54	0.34	0.41	8.15
Polar 1	0.49	0.57	0.26	0.34	9.74
Polar 2	0.53	0.61	0.37	0.46	10.5

Further development of IRFS instrument series

IRFS-3: preliminary design (FTIR spectrometer for “Meteor-MP” satellite, LEO)

	IRFS-2	IRFS-3
1. Spectral range	5.0 – 15.0 μm	3.6 - 15.5 μm (SWIR included)
2. OPD range	$\pm 1,7 \text{ cm}$	$\pm 2 \text{ cm}$
3. IFOV size	30 km	12 km
4. FOV size	---	$50 \times 50 \text{ km}^2$ (1 central + 4 corner elements)
5. Swath width	up to 2500 km	2200 km (28 x-track FOVs)
6. Radiometric uncertainty	0,5 K	0,5 K
7. NESR, NEdT	$3 \cdot 10^{-4} - 15 \mu\text{m}$, $1 \cdot 10^{-4} - 13 \mu\text{m}$ $3 \cdot 10^{-4} - 6 \mu\text{m}$	0,5 K – 15 μm , 0,6 K – 5,7 μm $3 \cdot 10^{-4} - 4,2 \mu\text{m}$
8. Spectral uncertainty	not specified	5 ppm
9. IFG time	0,5 s	0,2 s
10. Weight	50 kg	150 kg
11. Power	50 W	200 W
12. Data rate	600 Kb/s	< 3,5 Mb/s

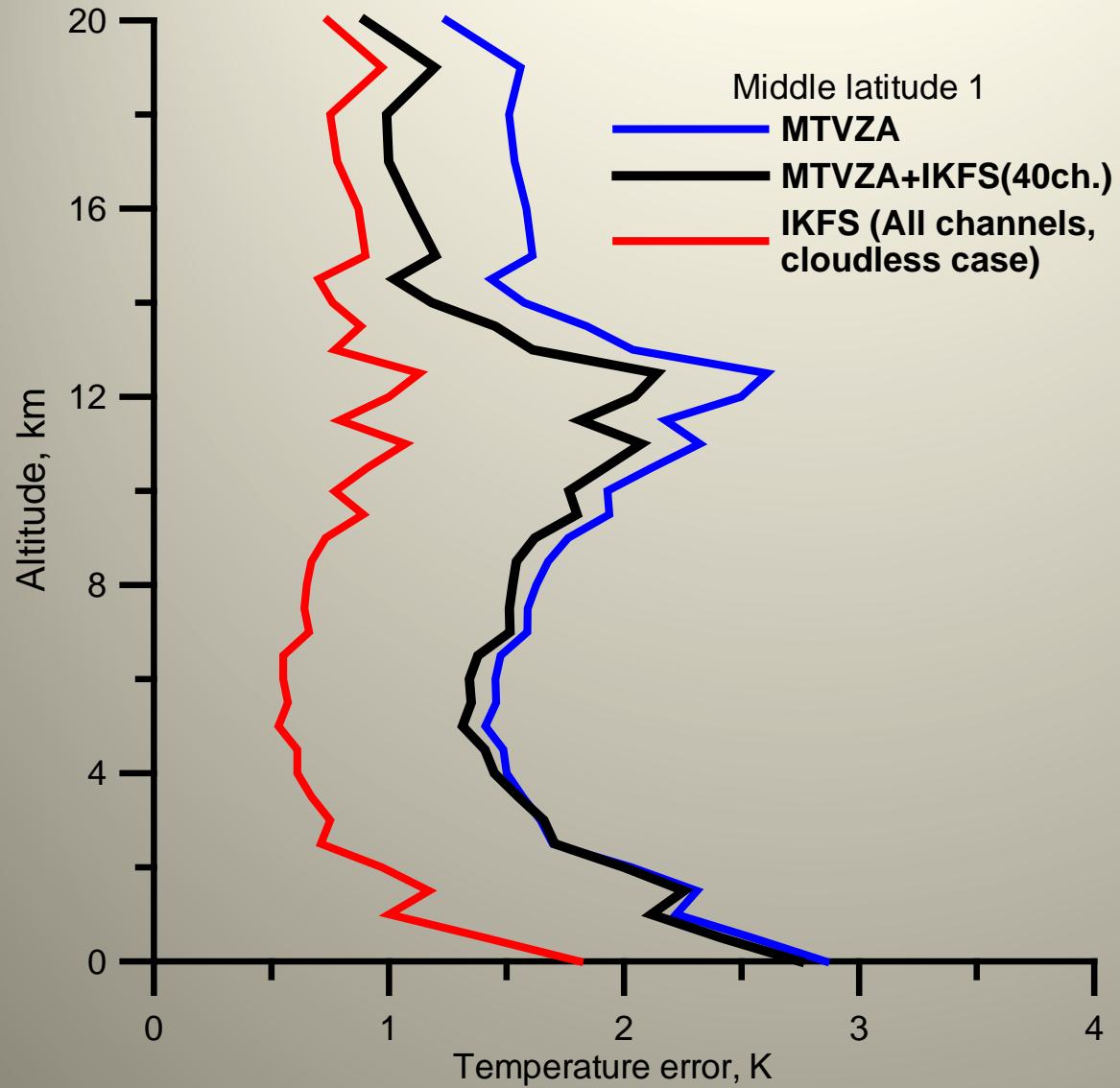
IKFS-GS: preliminary design (FTIR spectrometer for “Elektro-M” satellite, GEO)

Spectral range	LWIR: 680-1210 cm ⁻¹ (8,26...14,7 μm) MWIR: 1600...2250 cm ⁻¹ (4,44...6,25 μm)
Footprint	4 km
Operation modes	global coverage (< 60 min) regional coverage
Spectral resolution (1/2MPD)	0,5 cm ⁻¹
Radiometric accuracy (NEdT @ 280 K)	LWIR: 0,3-1 K MWIR: 0,3...1,8 K
Radiometric calibration uncertainty	0.5 K
Spectral uncertainty	5 ppm
Detector	160 x 160, 90 μm pixel, T = 55...60 K
Integration time	10 s
Mass	250-300 kg
Power	350 W
Data rate	150 Mb/s

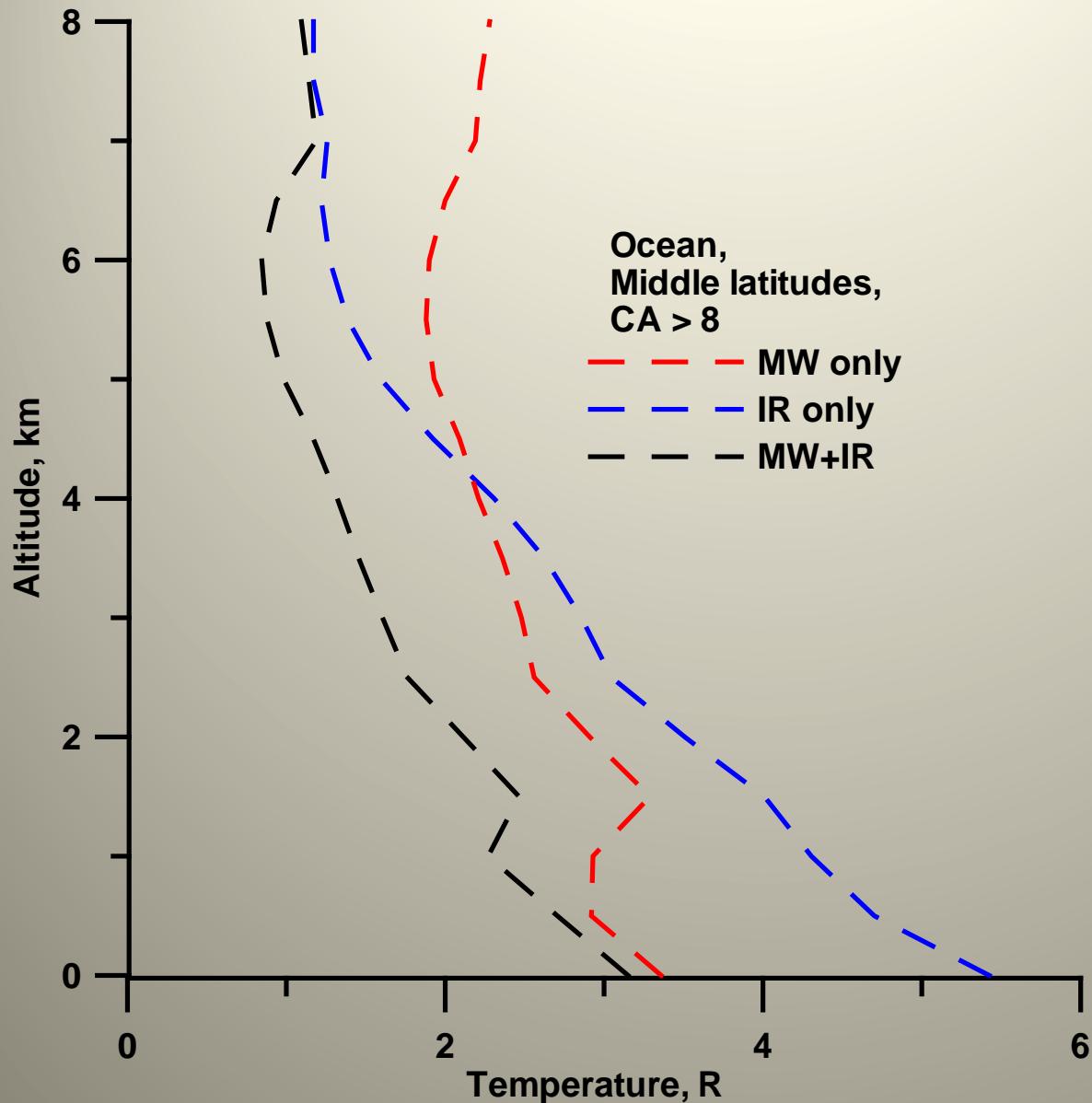
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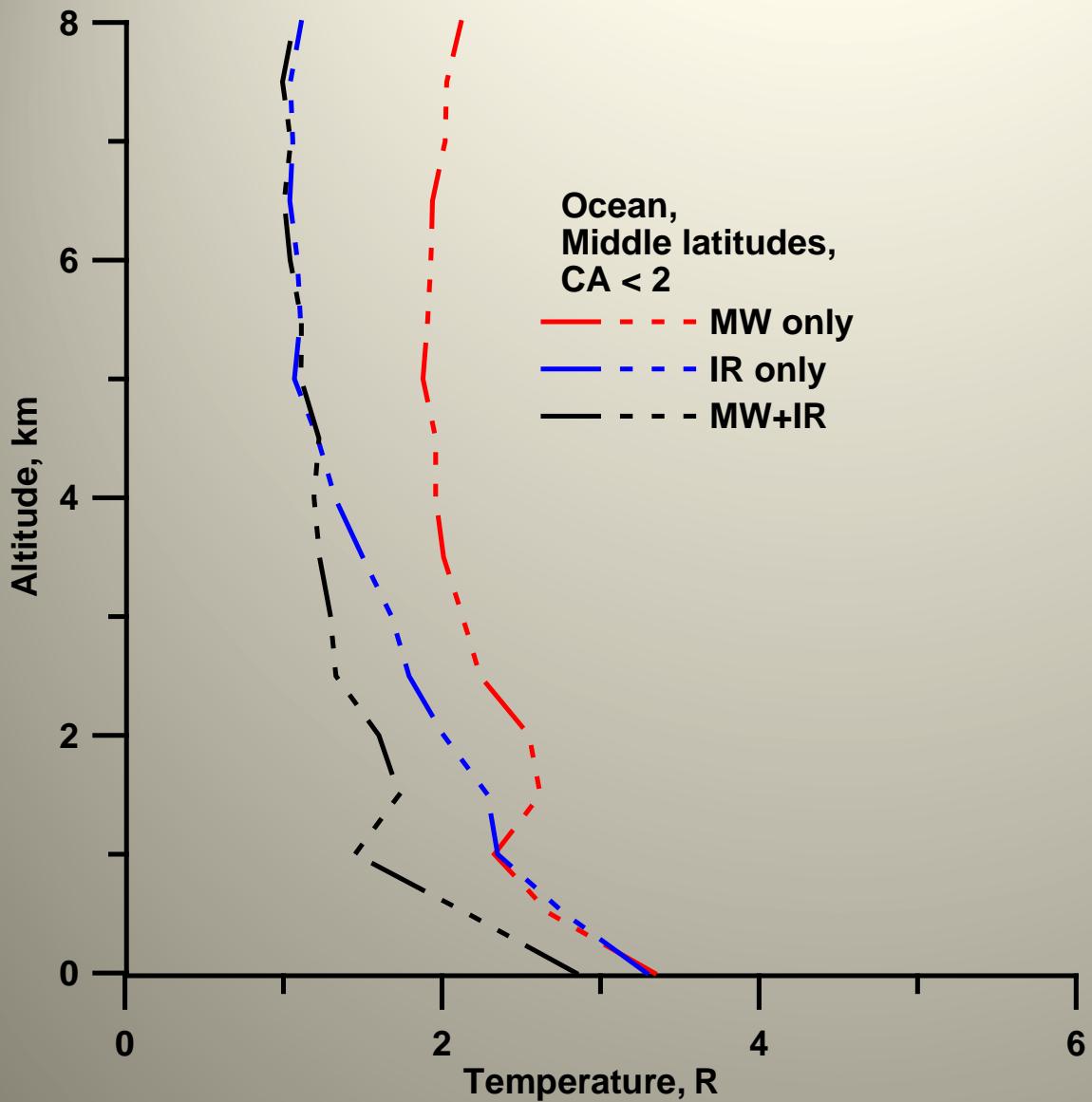
Thank you for your attention



Errors of retrieval the temperature profile from
- IR all channels (clear atmosphere)
- MW,
- MW+IR 40 channels, (cloudy atmosphere)
measurements.
Middle latitudes.



Errors of retrieval the
temperature profile
from
- MW,
- IR (all selected
channels)
- MW+IR (all selected
channels)
measurements.
Middle latitudes.
Cloudy atmosphere,
CA > 8.



Errors of retrieval the temperature profile from

- MW,
- IR (all selected channels)
- MW+IR (all selected channels)

measurements.
Middle latitudes.
Slightly cloudy atmosphere,
CA < 2.

Water vapor mixing ratio profile retrieval error statistics

Both training and retrieved sets are extracted from TIGR database

