First lessons learnt from Metop

Peter Schlüssel

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Initial Joint Polar System

- Since 1978 NOAA is flying operational polar orbiting weather satellites carrying multi-spectral sounders and imagers

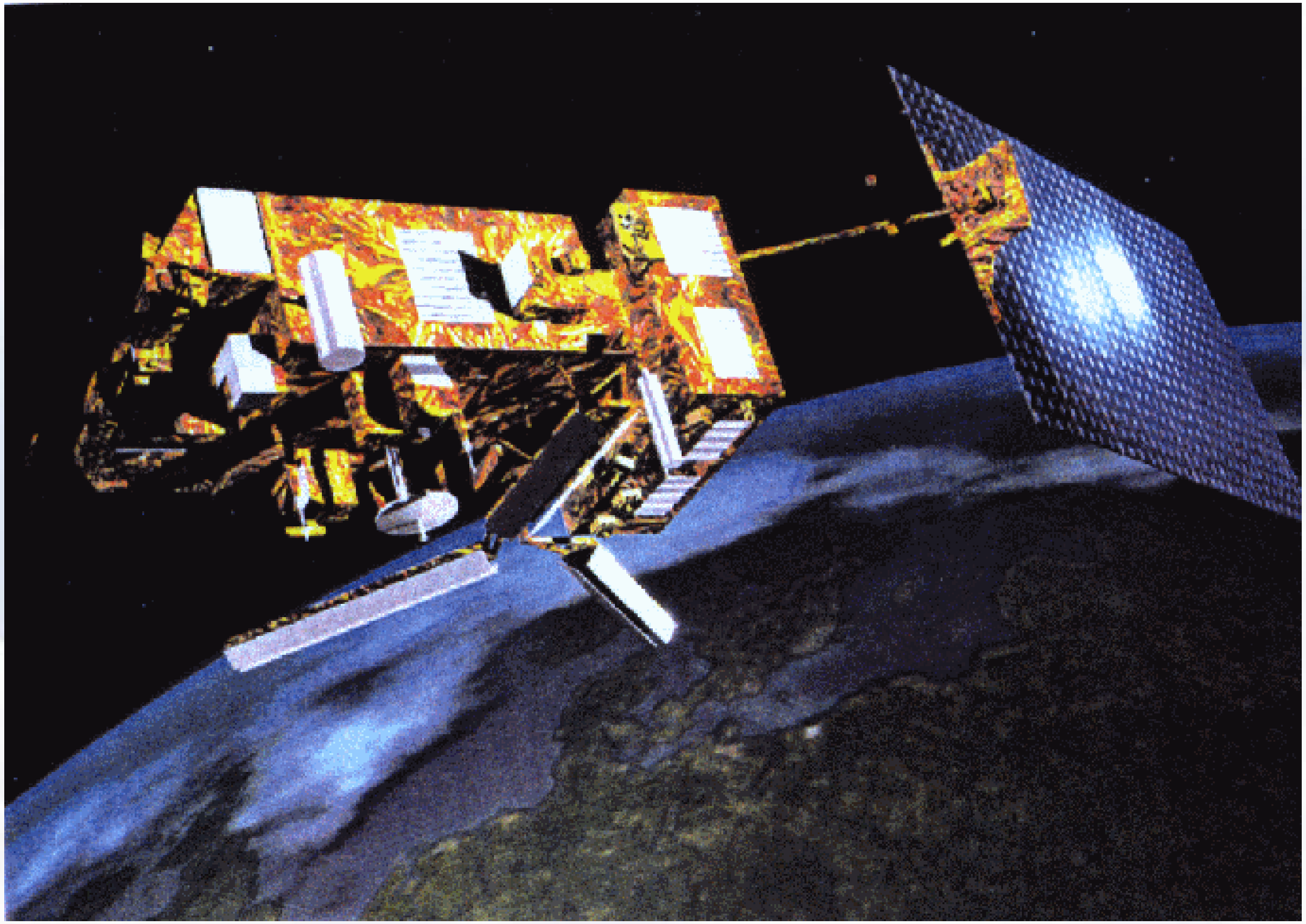
- Under a NOAA-EUMETSAT cooperation agreement, signed in November 1998, Europe agreed to share the burden of the meteorological polar service with the USA

- Integration and coordination of the NOAA Polar Orbiting Environmental Satellite (POES) and the EUMETSAT Polar System (EPS) Programmes:
  - Afternoon & early morning orbits covered by the USA (POES & DMSP Satellites)
  - Mid-morning orbit covered by Europe (Metop Satellites)
  - Exchange of instruments and data, coordinated development and operations

- Joint effort in a partnership of ESA, NOAA, CNES, and EUMETSAT

Start from Cosmodrome in Baikonour
with Sojuz/Fregat launcher on 19 October 2006

…overpass of Metop,
observed by Dieter Klaes on 19 April 2007



Height: 6.3 m
Transverse Section:
3.4 m x 3.4 m
(Launch Configuration)

Solar Panel: 11.3 m

Power: 2210 W
(End of Life, Orbit Average)

Lifetime: 5 Years

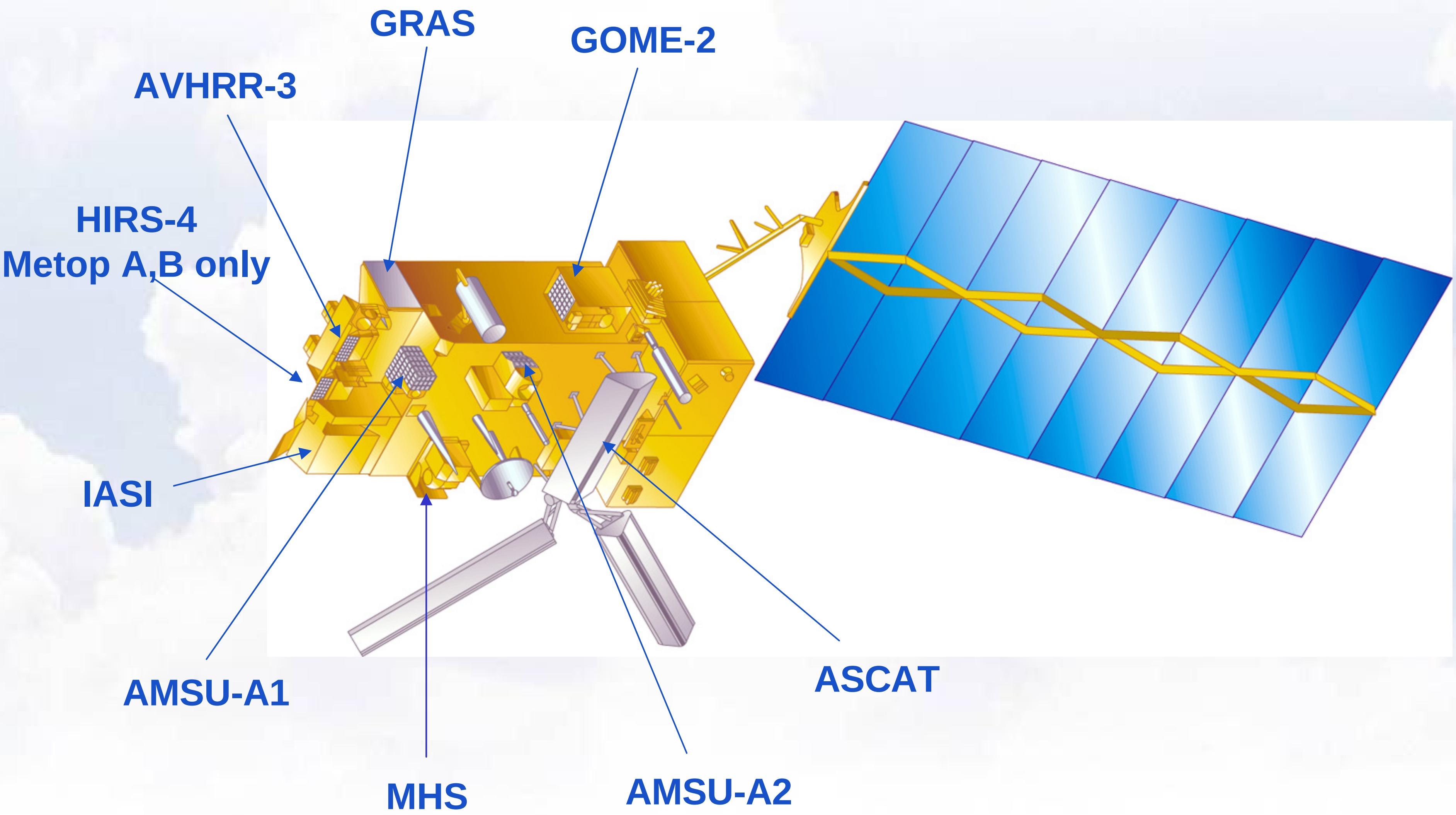
12 Instruments

Launch Mass: 4200 kg

Data Flow: 3500 kbps

The Metop Satellite

Metop: Satellite and Met-Instruments



Metop during integration of instruments

From launch to operational use (1/2)

- Launch on 19 October 2006 from Cosmodrome in Baikonur
  - Start and transfer to final orbit by ESA/ESOC
  - Handover to EUMETSAT: 22 October 2006
- Successive switch-on of instruments and distribution of data
  - SARR, SARP instrument switch on: 24 October 2006
  - AMSU-A1/A2 instrument switch-on: 24 October 2006
  - First global AMSU-A data distributed in NRT: 31 October 2006
  - IASI instrument switch-on and start of otgassing: 24 October 2006
  - AVHRR instrument switch-on and outgassing: 25 October 2006
  - First generation of AVHRR L1 products (VIS, NIR): 25 October 2006
  - HIRS instrument switch-on and outgassing: 26 October 2006
  - A-DCS instrument switch-on: 26 October 2006
  - GRAS instrument switch-on: 27 October 2006
  - ASCAT instrument switch-on and first product generated: 27 October 2006

From launch to operational use (2/3)

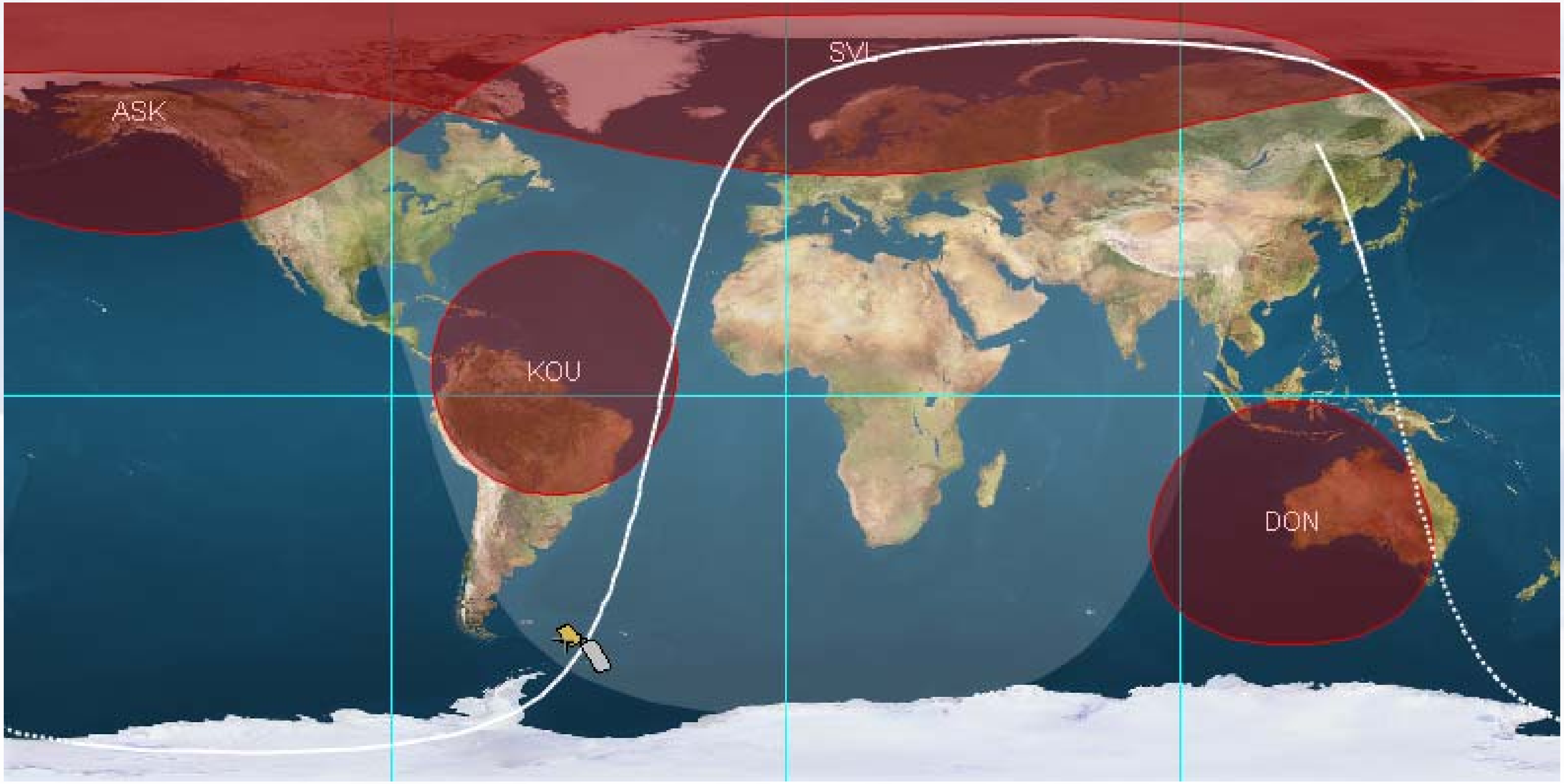
- Successive switch-on of instruments and distribution of data (cont.)
  - GOME-2 instrument switch-on: 27 October 2006
  - GOME-2 first spectra: 30 October 2006
  - MHS instrument switch-on and first data: 31 October 2006
  - MHS first L1 products generated: 1 November 2006
  - SEM instrument switch-on: 9 november 2006
  - ASCAT in measurement mode: 20 November 2006
  - A-DCS instrument switch-on: 20 November 2006
  - AVHRR, HIRS, GOME-2 in measurement mode:
  - LRPT switch-on: 15 January 2007
  - AHRPT switch-on: 23 January 2007
  - LRPT switch-off permanently (RFI with HIRS): 26 January 2006
- 4 November 2006: Two anomalies abruptly stopped the sequence of success
  - Sudden failure within the Low Resolution Picture Transmitter (LRPT)
  - Sudden automatic switch-off of the complete Metop-A Payload Module, with all instruments.

EUMETSAT

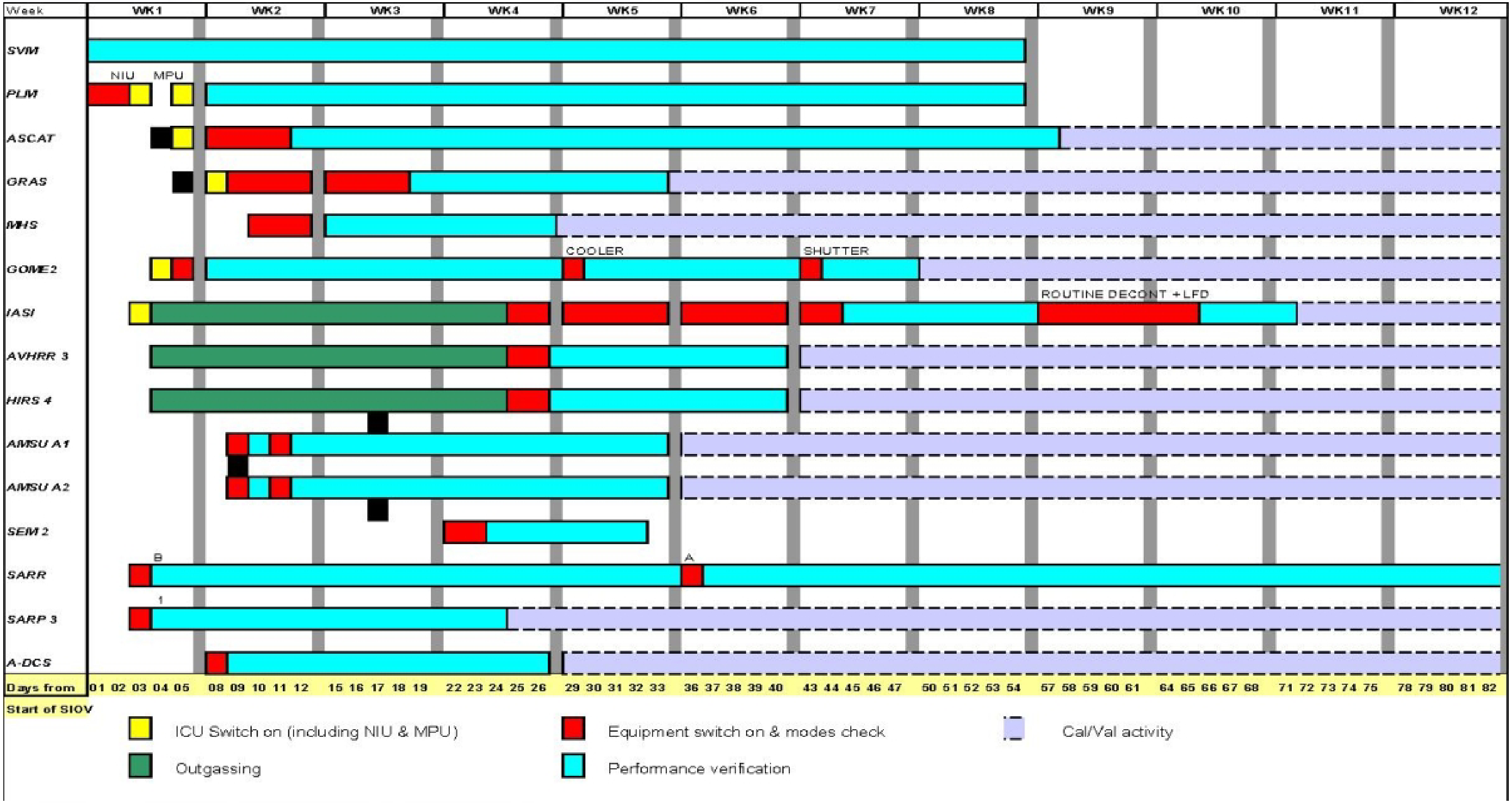
From launch to operational use (3/3)

- Progressive dissemination of data to users
  - Monitoring by NWP centres (ECMWF and Met Offcie) provides valuable information on data quality and anomalies
  - First global AMSU-A data distributed in NRT: 31 October 2006
  - Met Office starts assimilation of AMSU-A data on 22 January 2007
  - ECMWF starts assimilation of IASI data on 12 May 2007
  - Cooperation with OSI SAF leads to successful calibraton of ASCAT despite failure of calibration transponders
- Completion of Metop-A Satellite In-Orbit Verification (SIOV): 30 March 2007
- Hand-over to operations: 21 May 2007

Metop-A control during SIOV



Metop-A Satellite In-Orbit Verification



Validation

- Validation of processors and products
  - Configuration of Product Processing Facilities
  - First rough validation including bias corrections in Level 2 processors using short-range forecasts
  - Refinement wit data from dedicated validation campaigns
- Campaigns:
  - ASCAT transponder-campaign Turkey, November 2007
  - CNES/CNRS IASI-Balloon: Kiruna, February 2007
  - Met Office FAAM: Western North Sea, March2007
  - IfM/Polarstern: Atlantic Ocean, April/May 2007
  - Met Office/NASA FAAM and WB-57: Golf of Mexiko and Oklahoma ARM-Site, April/May 2007
  - DWD: Assmann-Observatory Lindenberg, June-August 2007
  - FMI: Observatory Sodankylä, June-August 2007
  - CNES/CNRS IASI-Balloon: Kiruna, September 2007
  - .
  - .

Partnership (1/2)

- The EPS programme was set up in partnership with
  - ESA (for the development of the Metop space Segment)
  - NOAA (provision of US instruments and operational cross support)
  - CNES-IASI (Development of the IASI instrument, level 1 processor and Technical Expertise Centre)
  - CNES-ARGOS (A-DCS payload and operations)

- The Space Segment development was managed by the Single Space Segment Team (SSST) located at ESTEC, Noordwijk

- The Metop-A satellite was developed by a European consortium led by Astrium as the prime contractor under a joint ESA-EUMETSAT contract

- The Launch service was provided by Starsem using a Soyuz 2.1 a with an ST fairing launcher from the Baikonur Cosmodrome, under EUMETSAT Contract

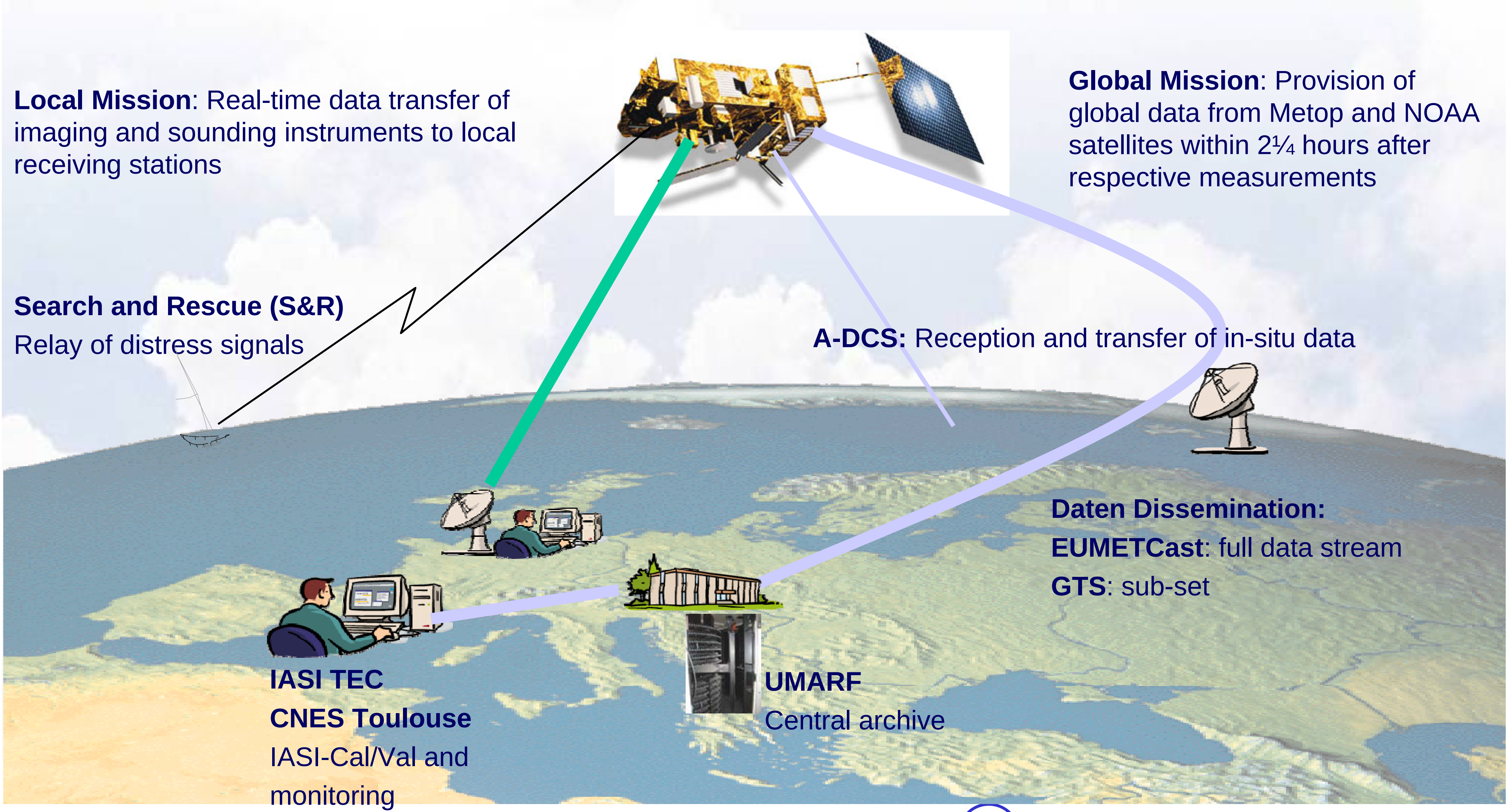
Partnership (2/2)

- The Launch and Early Operations Phase (LEOP) was conducted by ESOC, Darmstadt, under EUMETSAT contract
- The Core Ground Segment was developed by Thales Alenia Space under EUMETSAT contract
- The Satellite SIOV activities were conducted by a joint team led by the SSST, EUMETSAT being responsible for the operations, and with contributions from all other partner organisations and industrial teams from the space segment and instrument manufacturers
- Last but not least: EUMETSAT users provide valuable feedback
  - Throughout the programme development on instrument characteristics, system configurations, product processing and product formats
  - Post-launch via data monitoring and data usage

EUMETSAT

Satellite Application Facilities (SAF)

EPS Service


Local Mission: Real-time data transfer of imaging and sounding instruments to local receiving stations
Global Mission: Provision of global data from Metop and NOAA satellites within 2¼ hours after respective measurements
Search and Rescue (S&R)
Relay of distress signals
A-DCS: Reception and transfer of in-situ data
Daten Dissemination:
EUMETCast: full data stream
GTS: sub-set
IASI TEC
CNES Toulouse
IASI-Cal/Val and monitoring
UMARF
Central archive

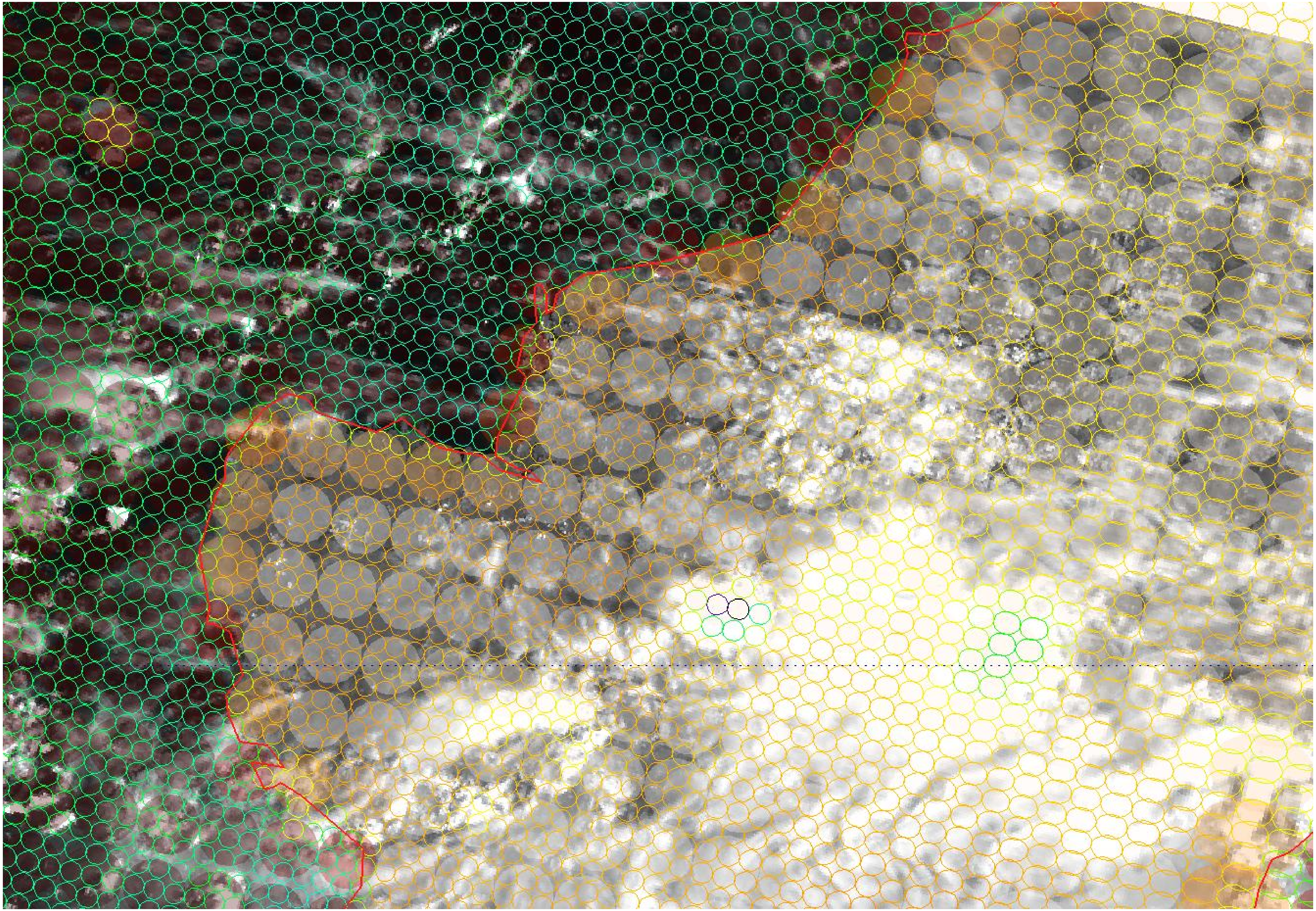
Data transfer and distribution

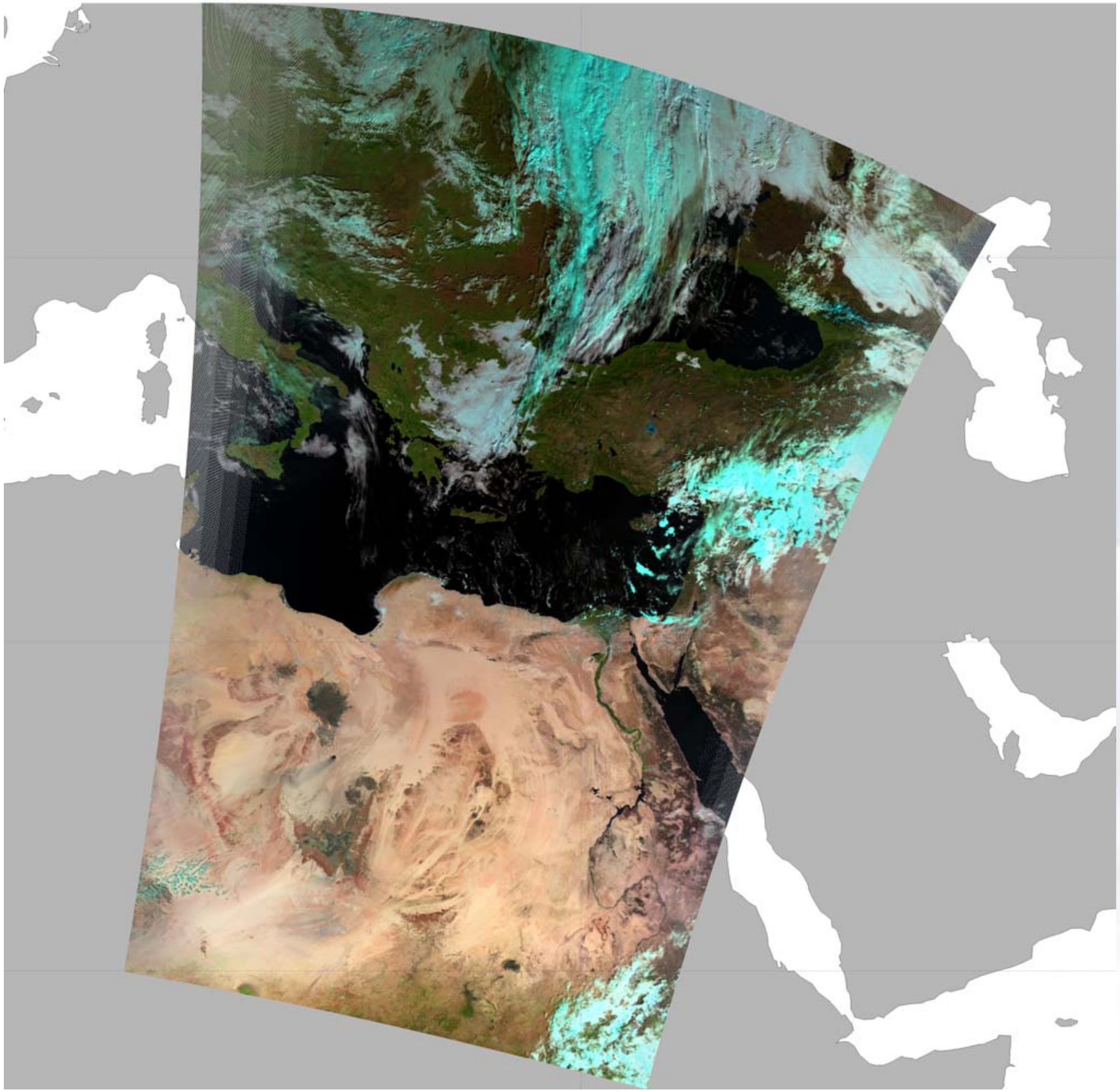
- From satellite to surface:
  - Data of one orbit is stored on board the satellite
  - Transfer to surface via X-band reception station on Svalbard after completion of each orbit
  - Transfer from Svalbard to Darmstadt via fibre link
  - Local users can directly read out the instrument data while the satellite is above their horizon

- Data processing in EPS Core Ground Segment at EUMETSAT HQ
  - Generation of Level-1-Products: decoding, calibration, navigation, apodisation, mapping/merging of data from different instruments
  - Generation of ATOVS and IASI Level-2-Products: atmospheric and surface meteorological parameters

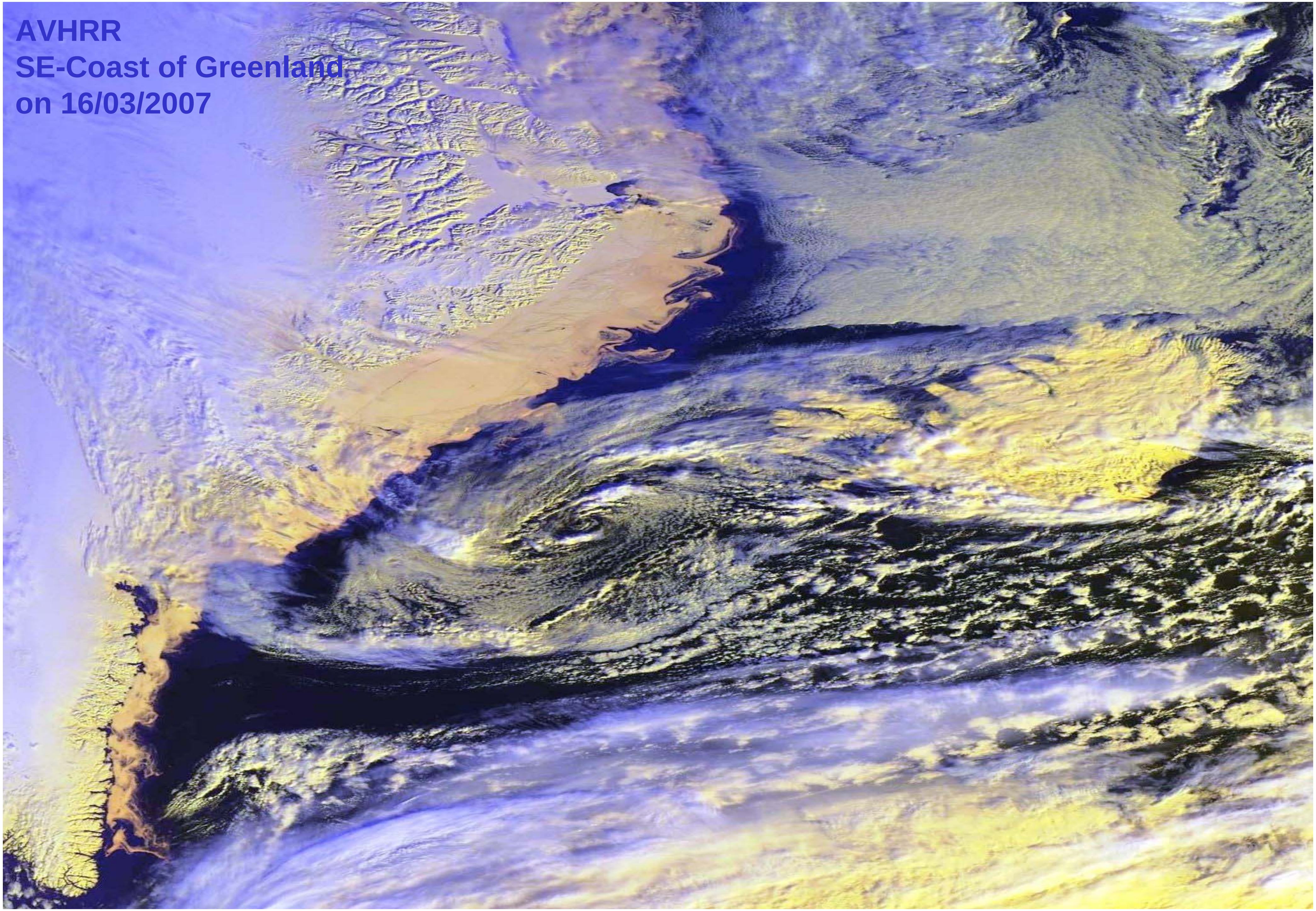
- Distribution to users:
  - Level 1: within 2¼ h after measurement, Level 2: within 3 h after measurement
  - Transfer via EUMETCast (BUFR code)
  - Transfer of subset via GTS (BUFR code)
  - All data, inclusive generated products are archived in the UMARF: Unified Archival and Retrieval Facility, and accessible 7 hours after the measurement

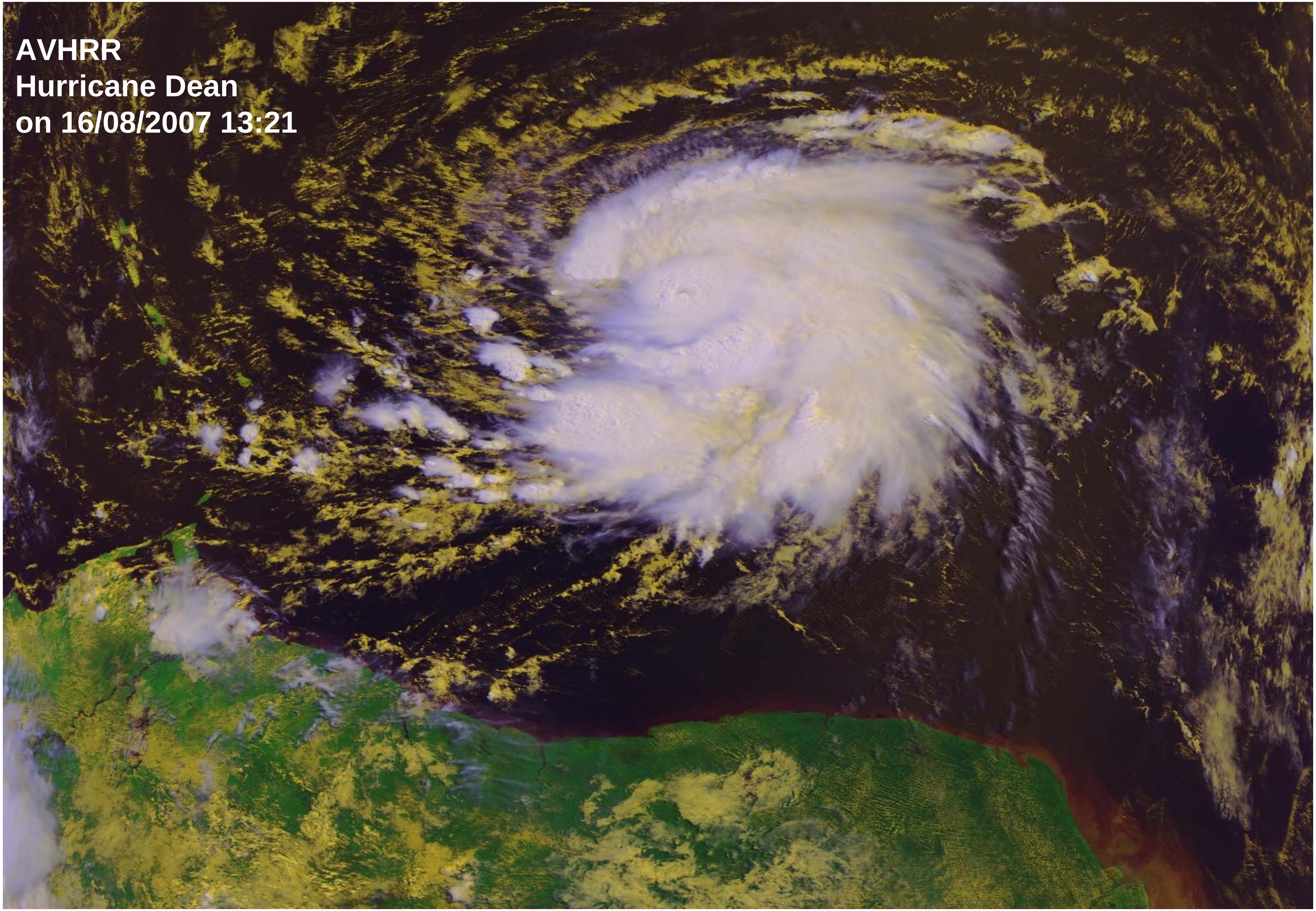

• ATOVS- and AVHRR-Products
– AVHRR: Advanced Very High Resolution Radiometer
– AMSU-A: Advanced Microwave Sounding Unit A
– MHS: Microwave Humidity Sounder
– HIRS: High-resolution Infrared Radiation Sounder

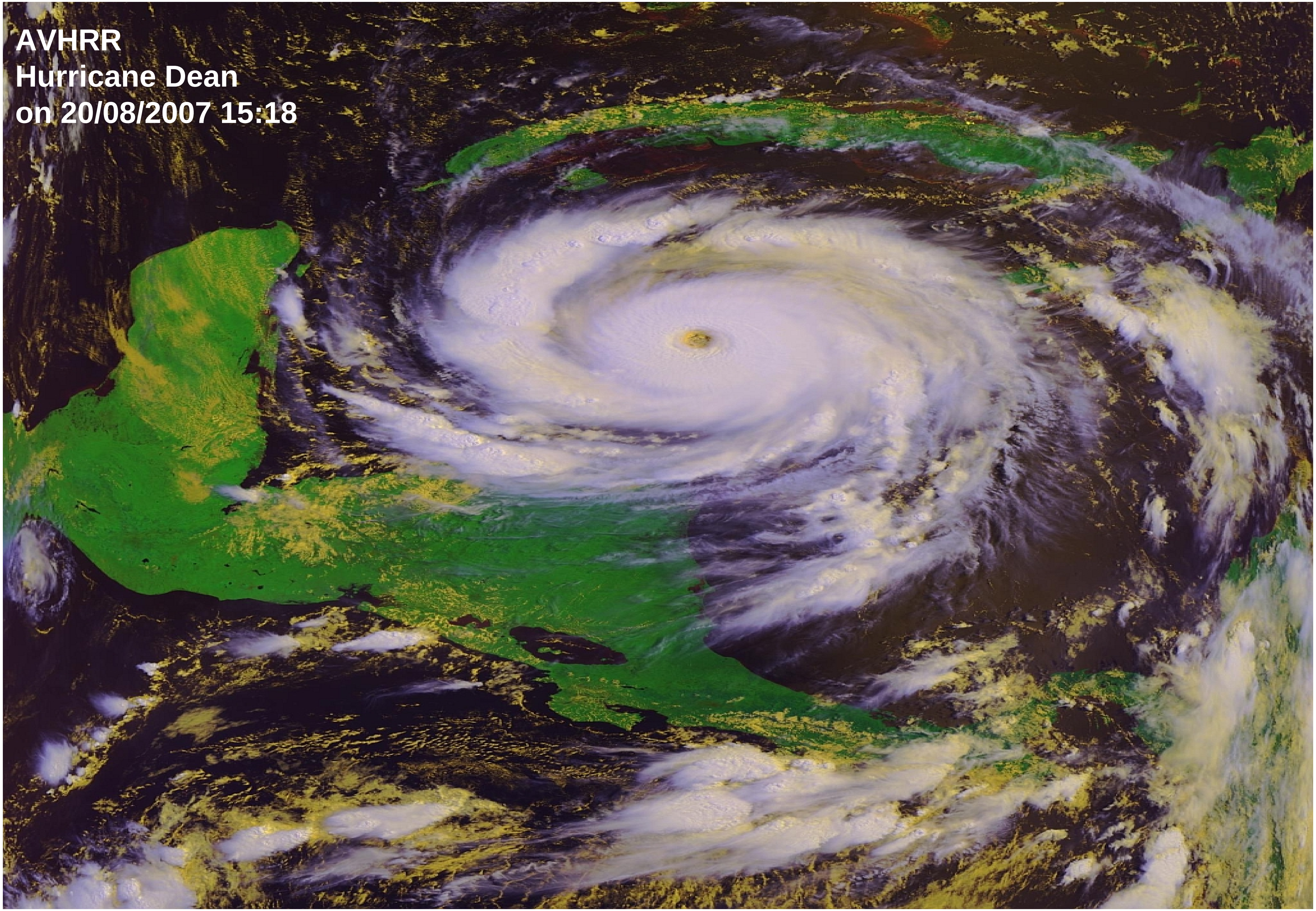




First AVHRR data on 25/10/2006

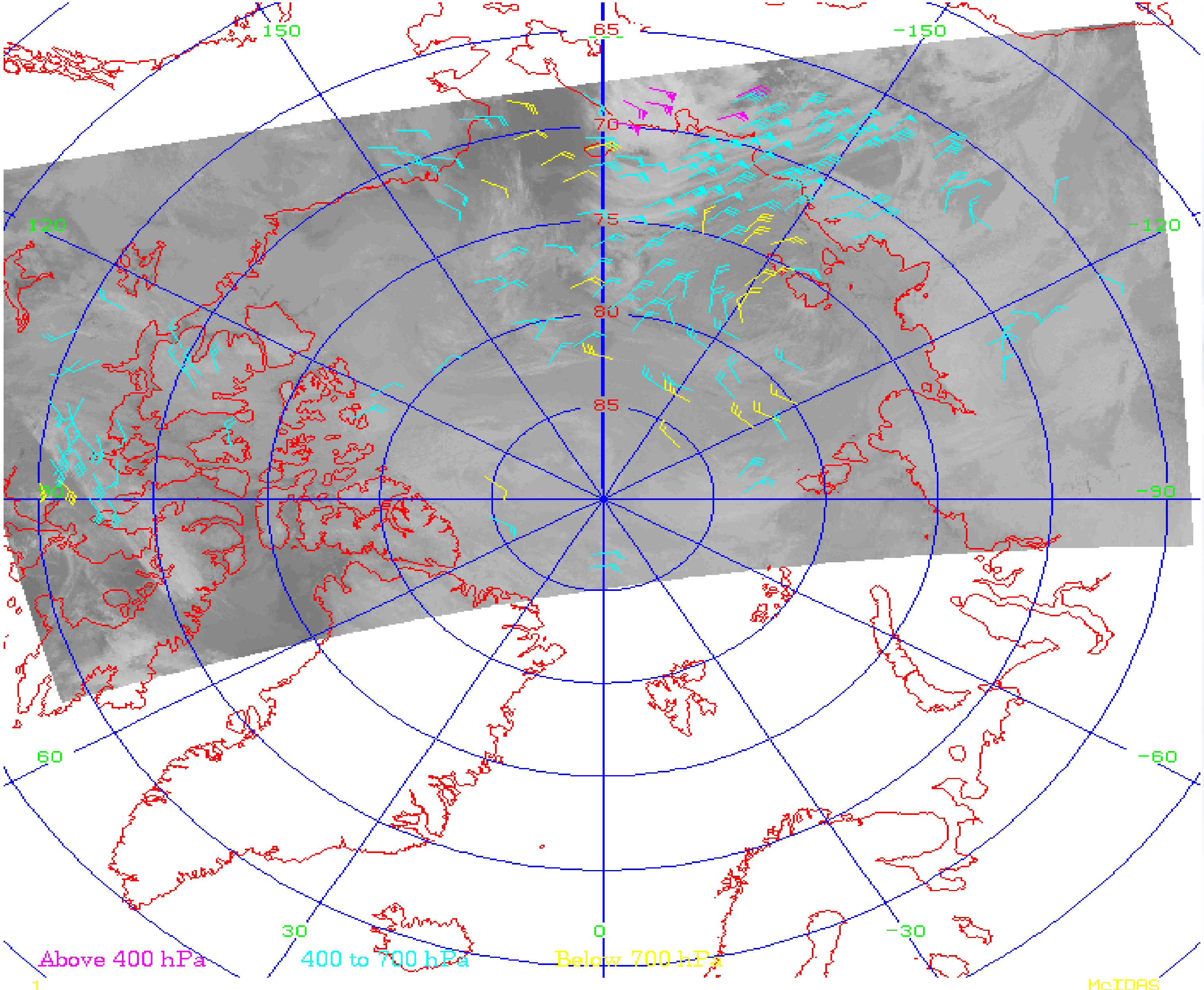

AVHRR
SE-Coast of Greenland
on 16/03/2007


AVHRR
Hurricane Dean
on 16/08/2007 13:21


AVHRR
Hurricane Dean
on 20/08/2007 15:18

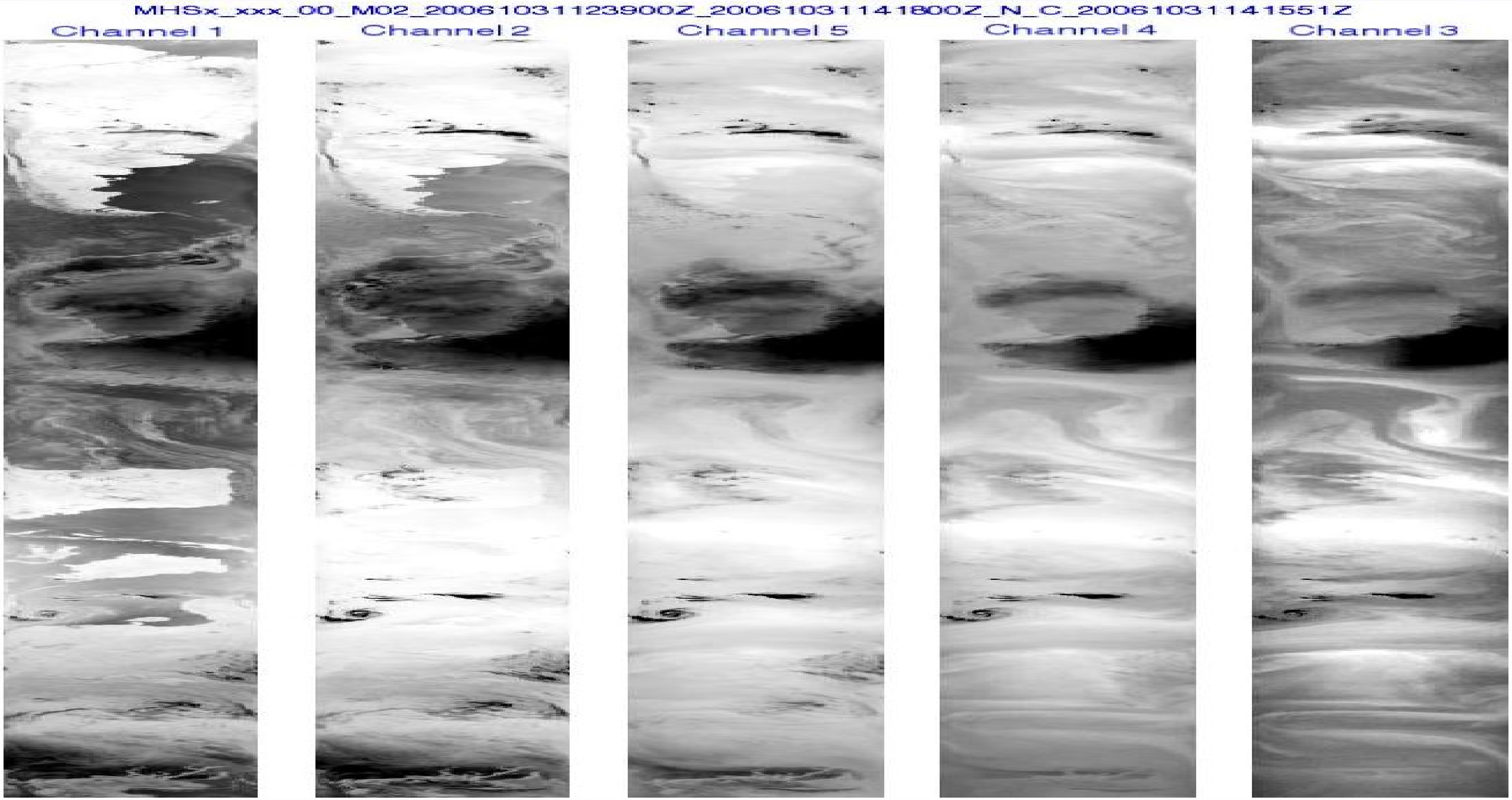
AVHRR:

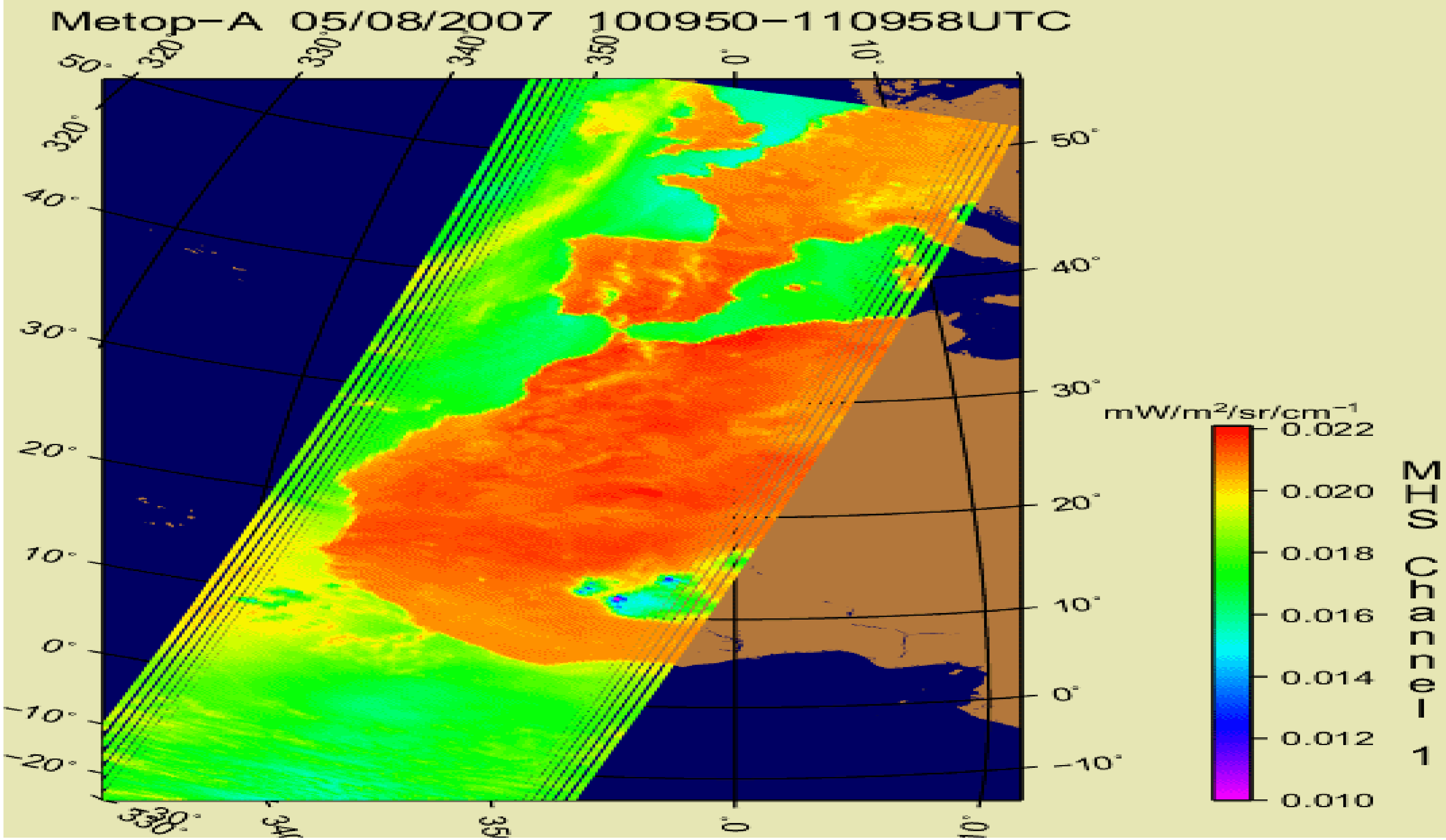
Wind vectors vectors in polar regions



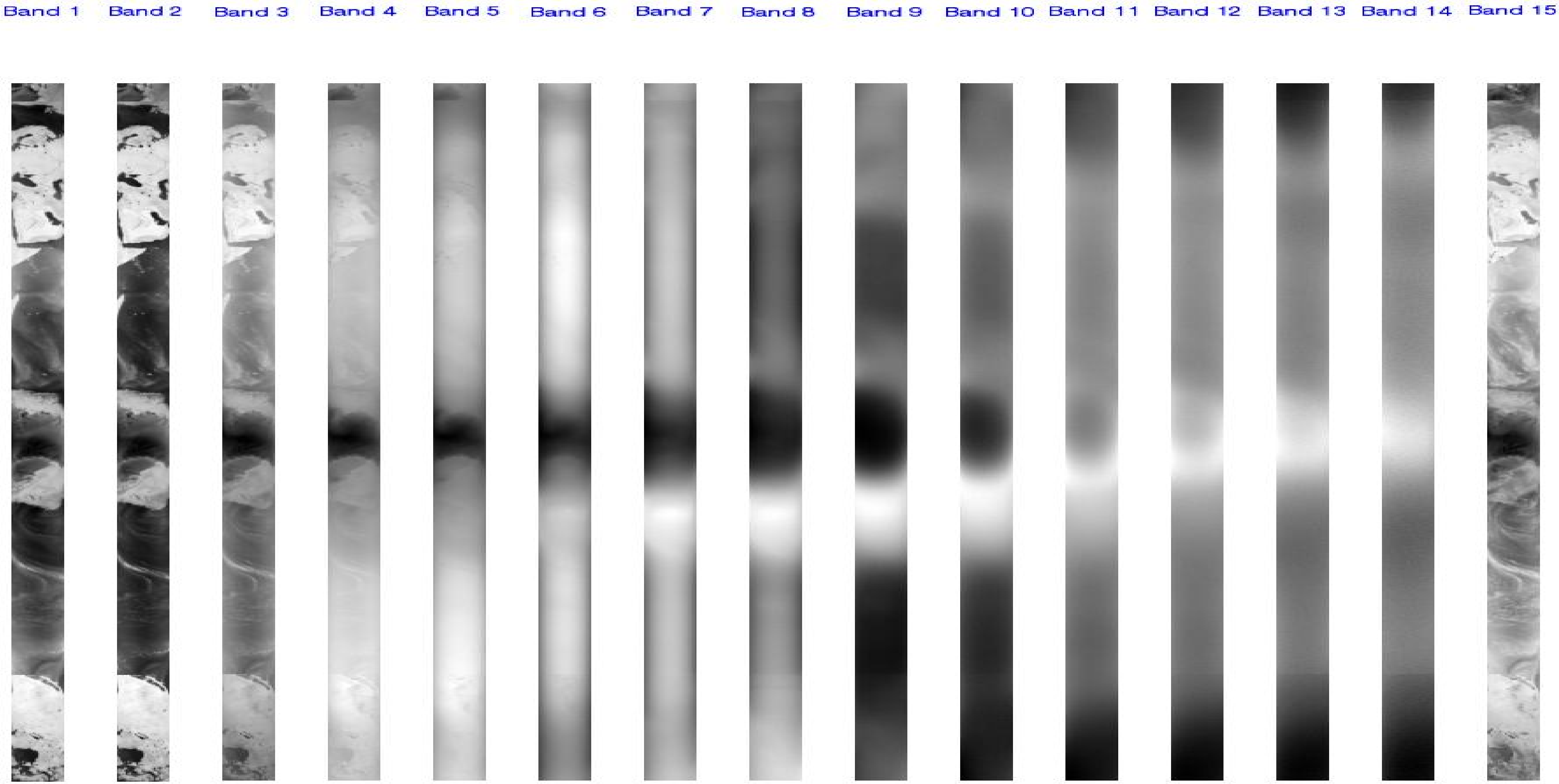
CIMSS/Univ. Wisconsin

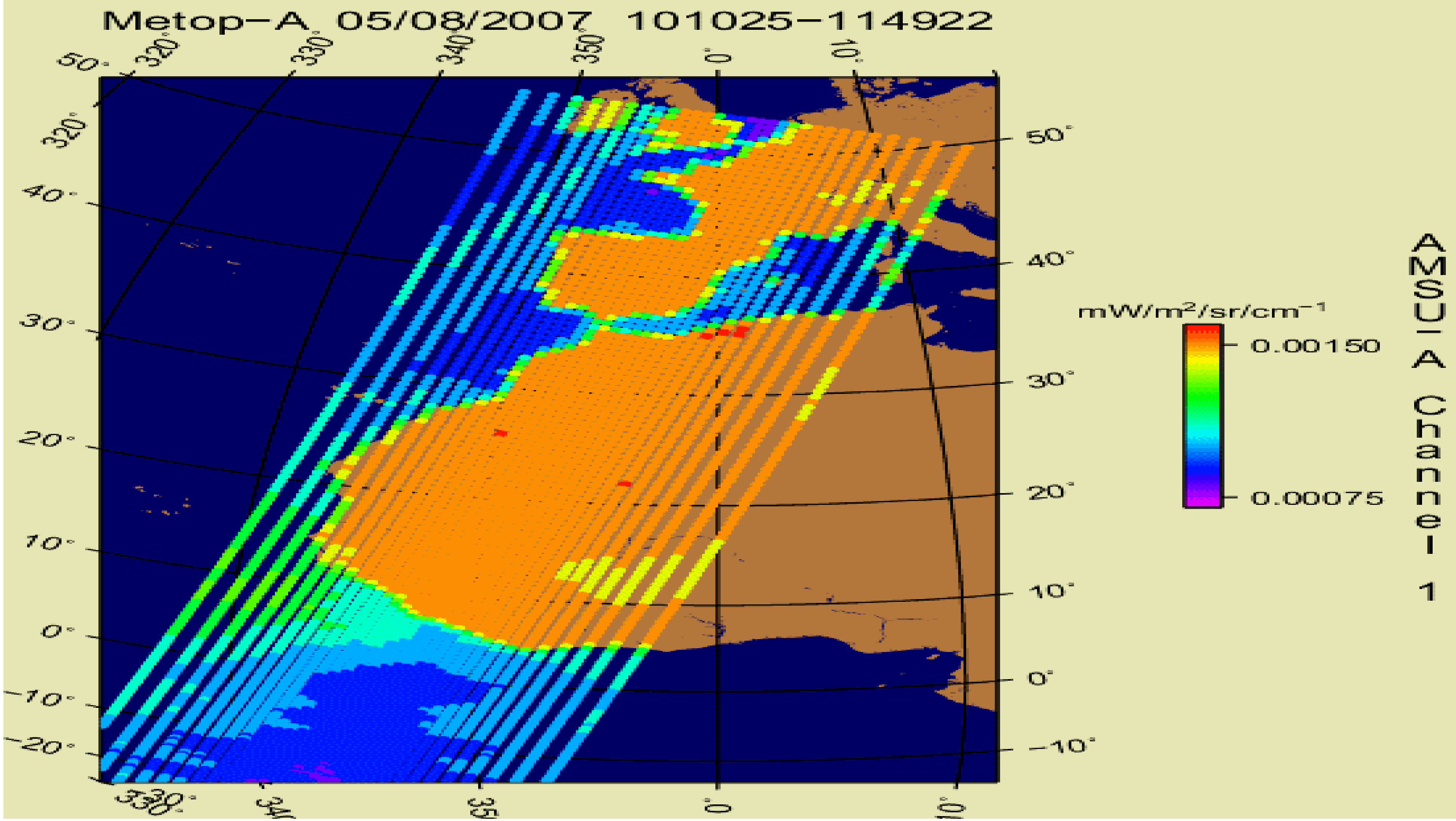
MHS


MHSx_xxx_00_M02_20061031123900Z_20061031141800Z_N_C_20061031141551Z
Channel 1
Channel 2
Channel 5
Channel 4
Channel 3


Metop−A 05/08/2007 100950−110958UTC
mW/m²/sr/cm⁻¹
0.022
0.020
0.018
0.016
0.014
0.012
0.010
MHS Channel 1
50°
40°
30°
20°
10°
0°
−10°
−20°
320°
330°
340°
350°
0°
10°

AMSU-A

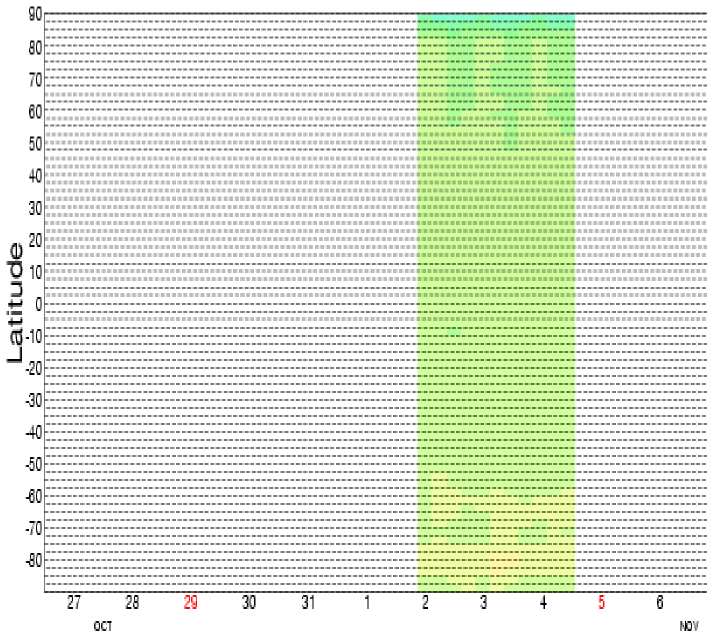

Band 1
Band 2
Band 3
Band 4
Band 5
Band 6
Band 7
Band 8
Band 9
Band 10
Band 11
Band 12
Band 13
Band 14
Band 15



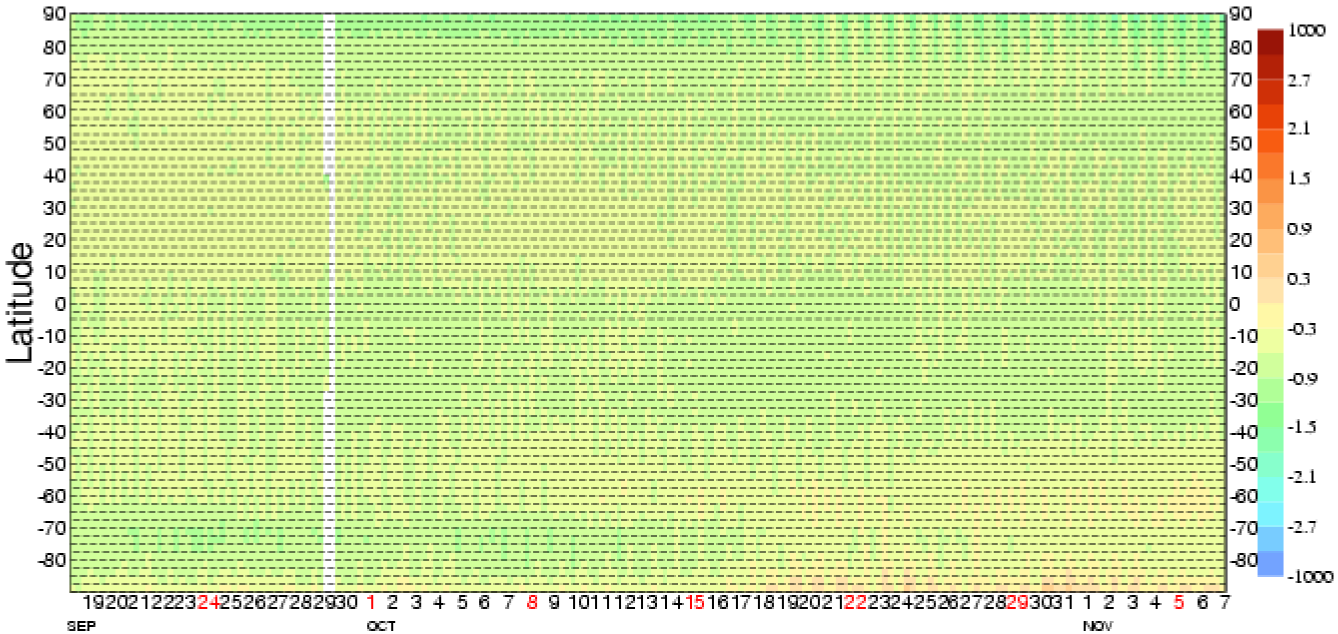
Metop-A 05/08/2007 101025-114922
mW/m²/sr/cm⁻¹
0.00150
0.00075
AMSU-A Channel 1

ECMWF monitoring the data from the beginning

STATISTICS FOR RADIANCES FROM METOP-A / AMSU-A
ZONAL MEAN FIRST GUESS DEPARTURE (OBS-FG) [K] (CLEAR)
CHANNEL = 10
EXP = 0001
Min: -1.9767 Max: -0.227095 Mean: -0.780668



STATISTICS FOR RADIANCES FROM NOAA-18 / AMSU-A
ZONAL MEAN FIRST GUESS DEPARTURE (OBS-FG) [K] (CLEAR)
CHANNEL = 10
EXP = 0001
Min: -1.607 Max: 0.465248 Mean: -0.607009



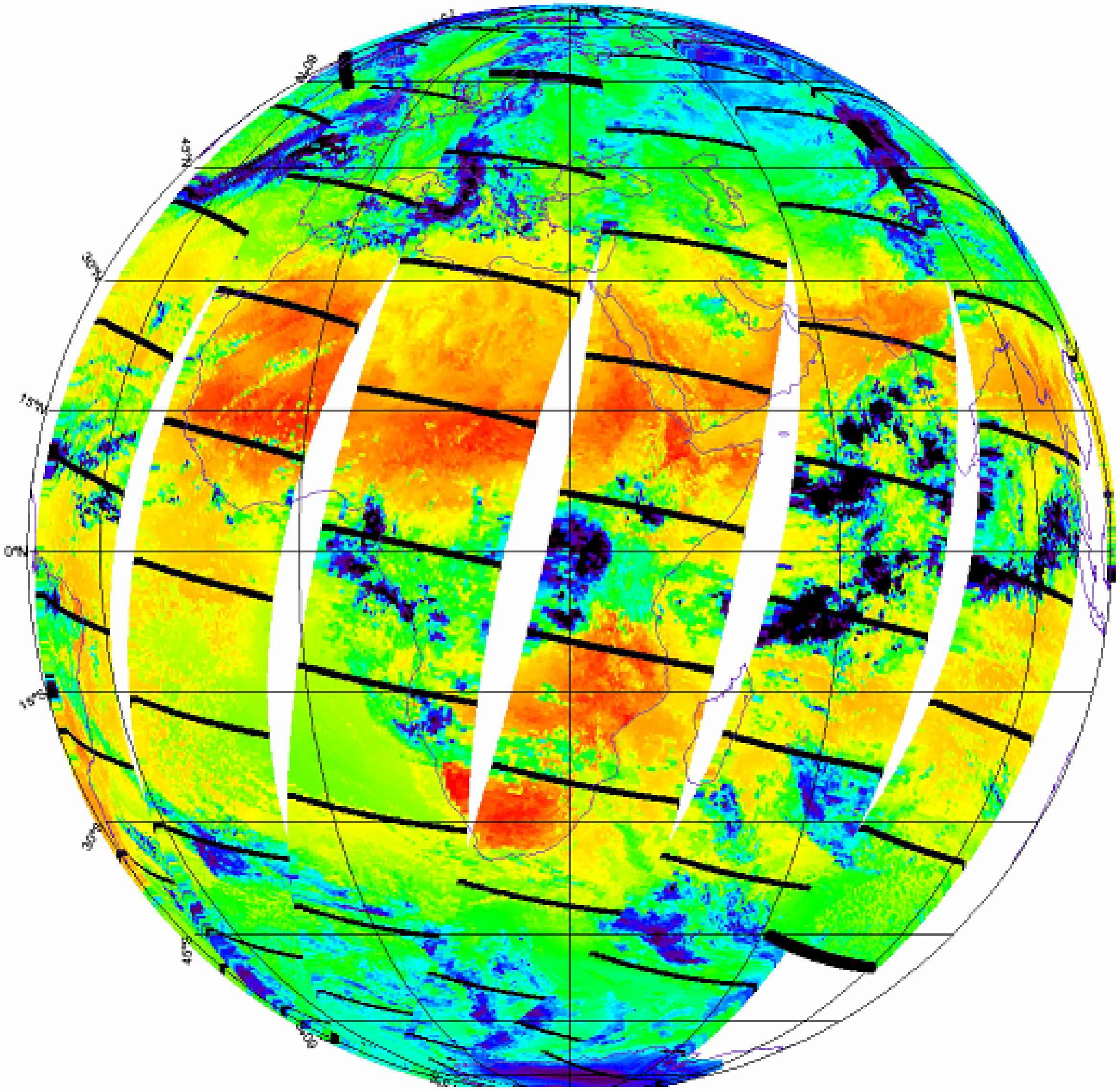
Feedback from Met Office
AMSU-A noise figures (NEΔT in K)

Channel	Spec	Met Office estimate	NOAA-18	Channel	Spec	Met Office estimate	NOAA-18
1	0.3	0.19	0.20	9	0.25	0.18	0.17
2	0.3	0.19	0.18	10	0.4	0.24	0.20
3	0.4	0.28	0.22	11	0.4	0.29	0.23
4	0.25	0.15	0.16	12	0.6	0.37	0.29
5	0.25	0.15	0.18	13	0.8	0.52	0.40
6	0.25	0.12	0.15	14	1.2	0.92	0.63
7	0.25	0.13	0.16	15	0.5	0.10	0.14
8	0.25	0.19	0.20				

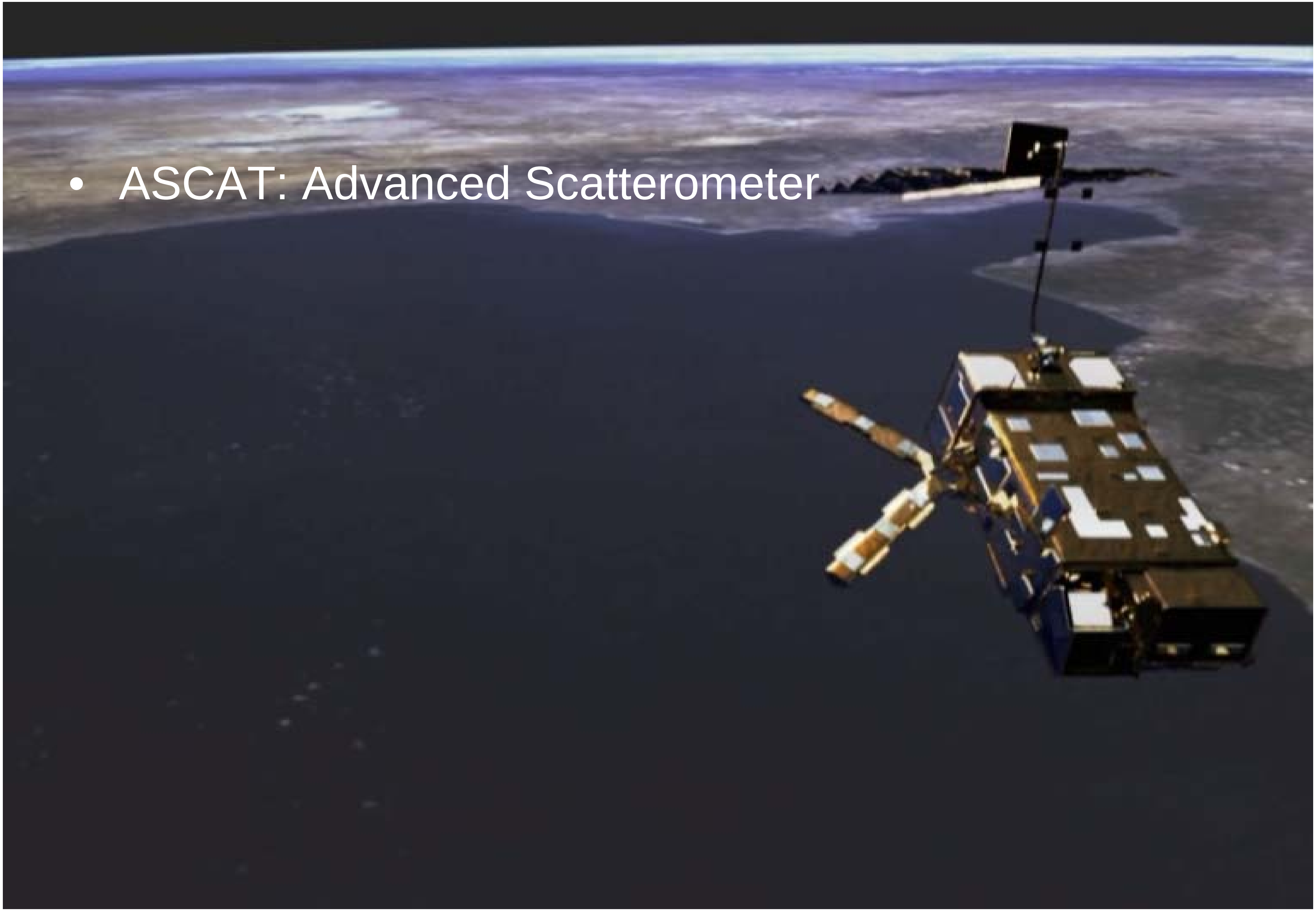
Feedback from Met Office
MHS noise figures (NEΔT in K)

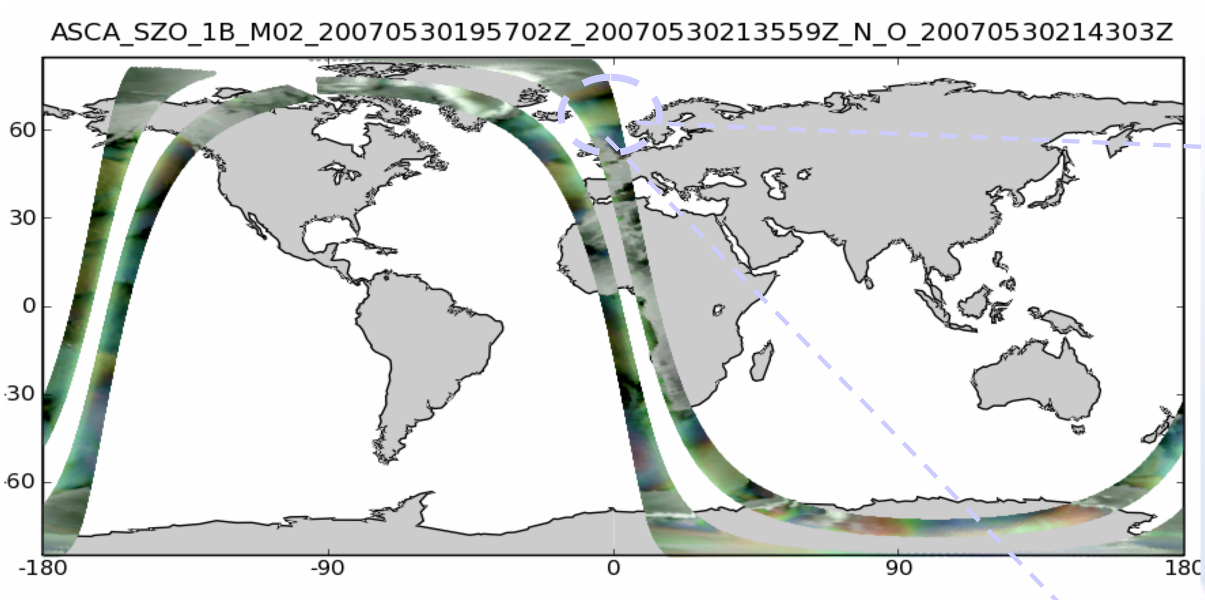
Channel	Spec	EUMETSAT estimate	Met Office estimate	NOAA-18 EUM / NOAA	AMSU-B EUM / NOAA
1	1.0	0.19	0.20	0.21/0.32	0.41/040
2	1.0	0.39	0.37	0.34/0.53	0.80/0.80
3	1.0	0.52	0.50	0.54/0.50	0.82/0.80
4	1.0	0.40	0.41	0.40/0.41	0.75/0.75
5	1.0	0.36	0.34	0.55/0.55	0.80/0.80

HIRS Channel 8

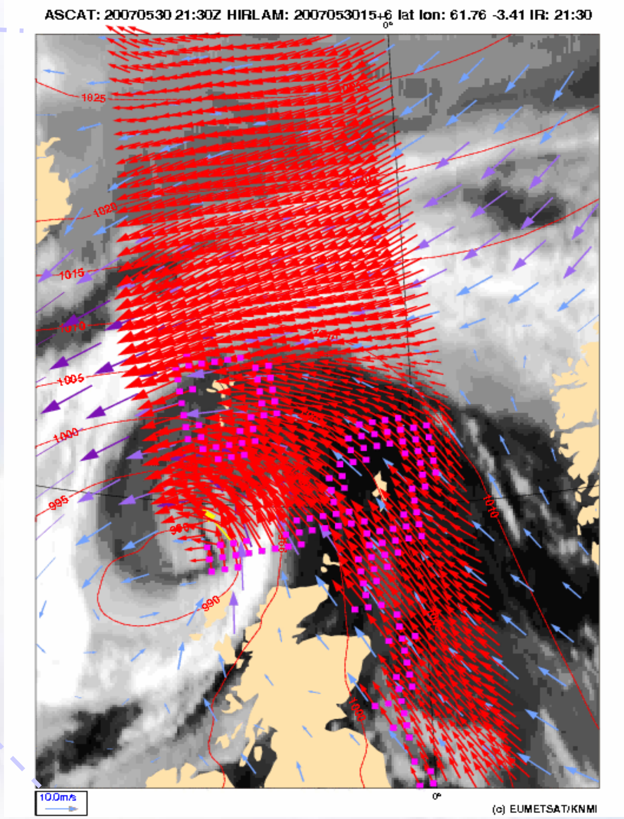


21 November 2006

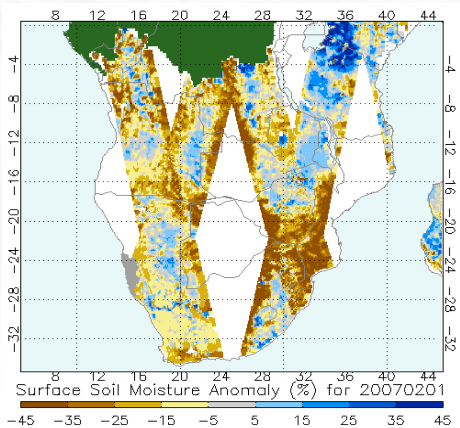

• ASCAT: Advanced Scatterometer



LEVEL 1b: Sigma0-triplets as RGB image



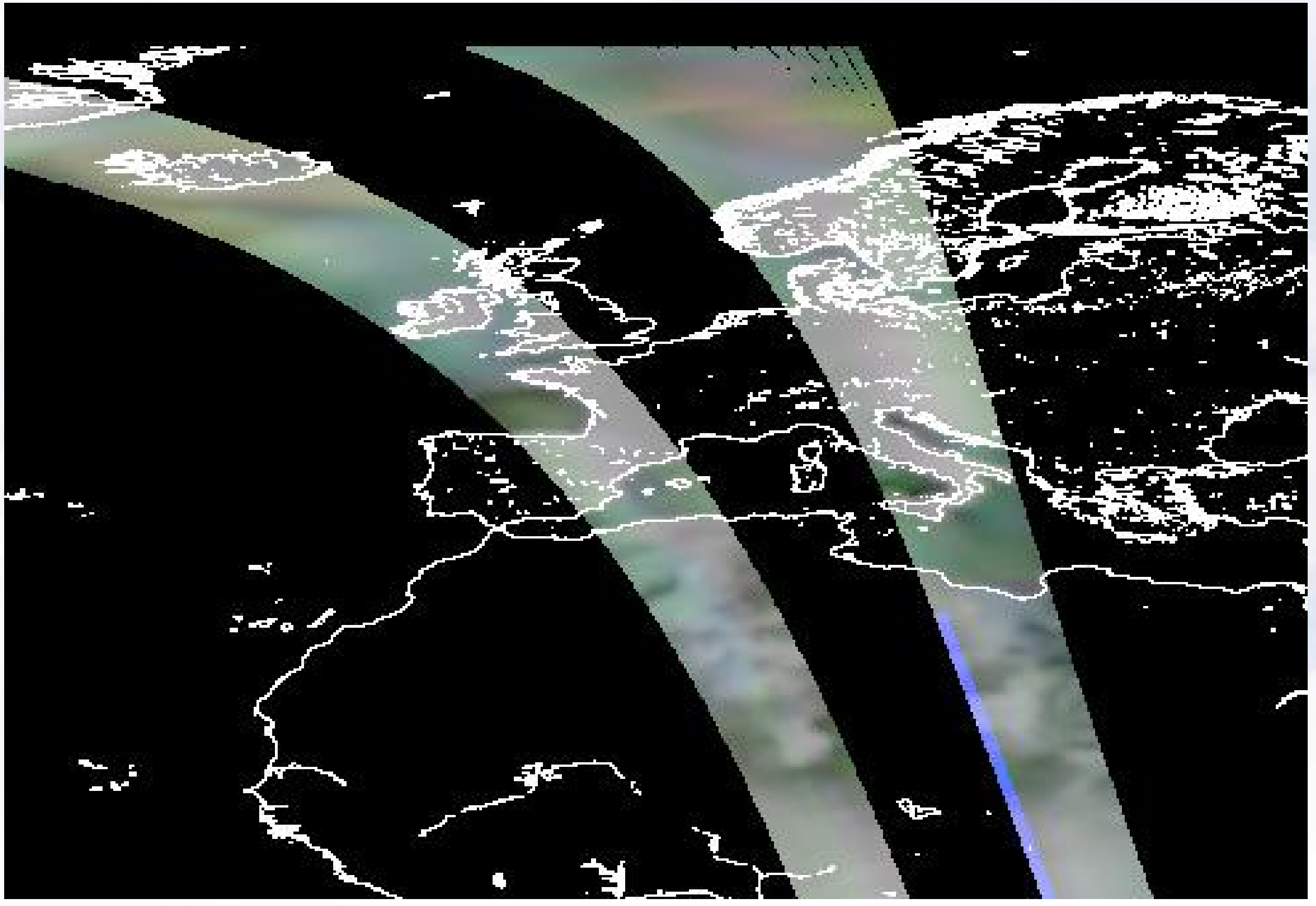
LEVEL 2: surface wind (ocean)



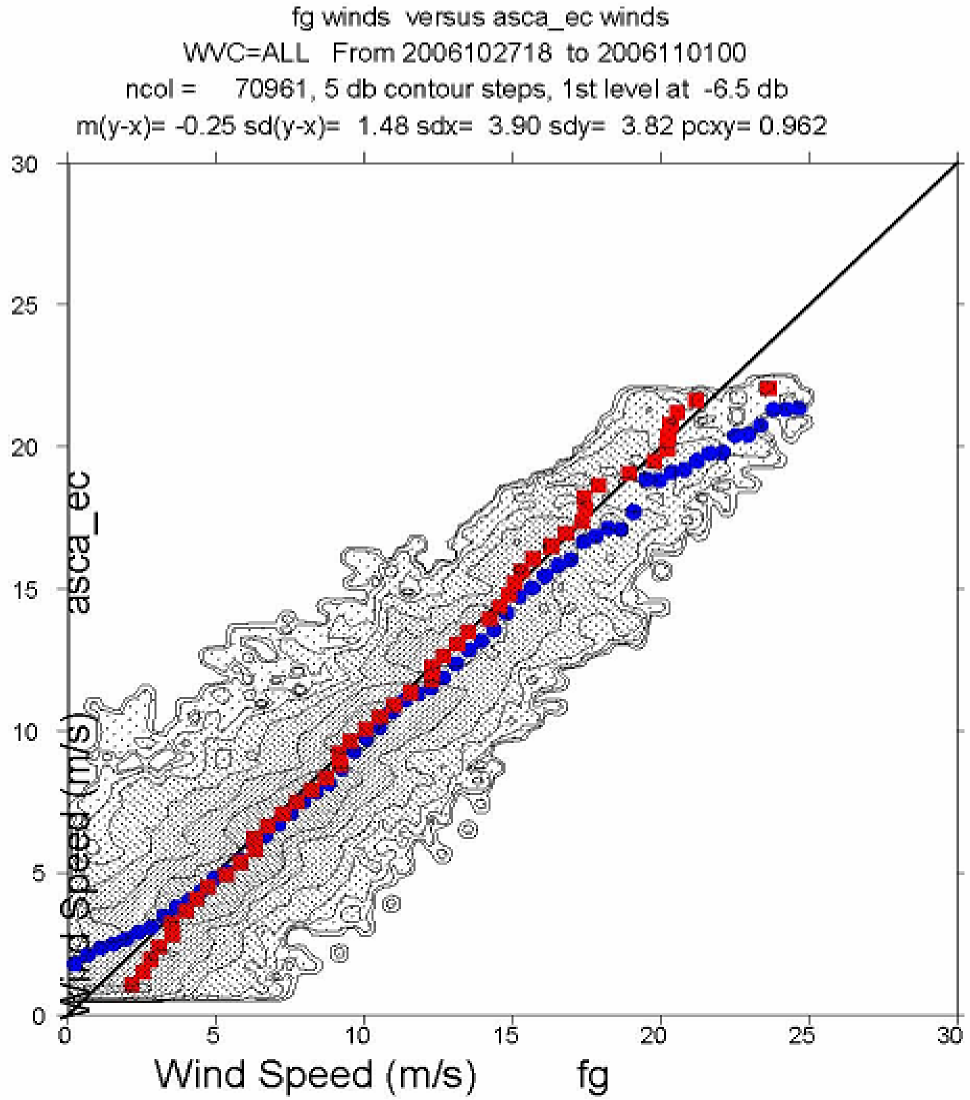
LEVEL 2: soil moisture (land)

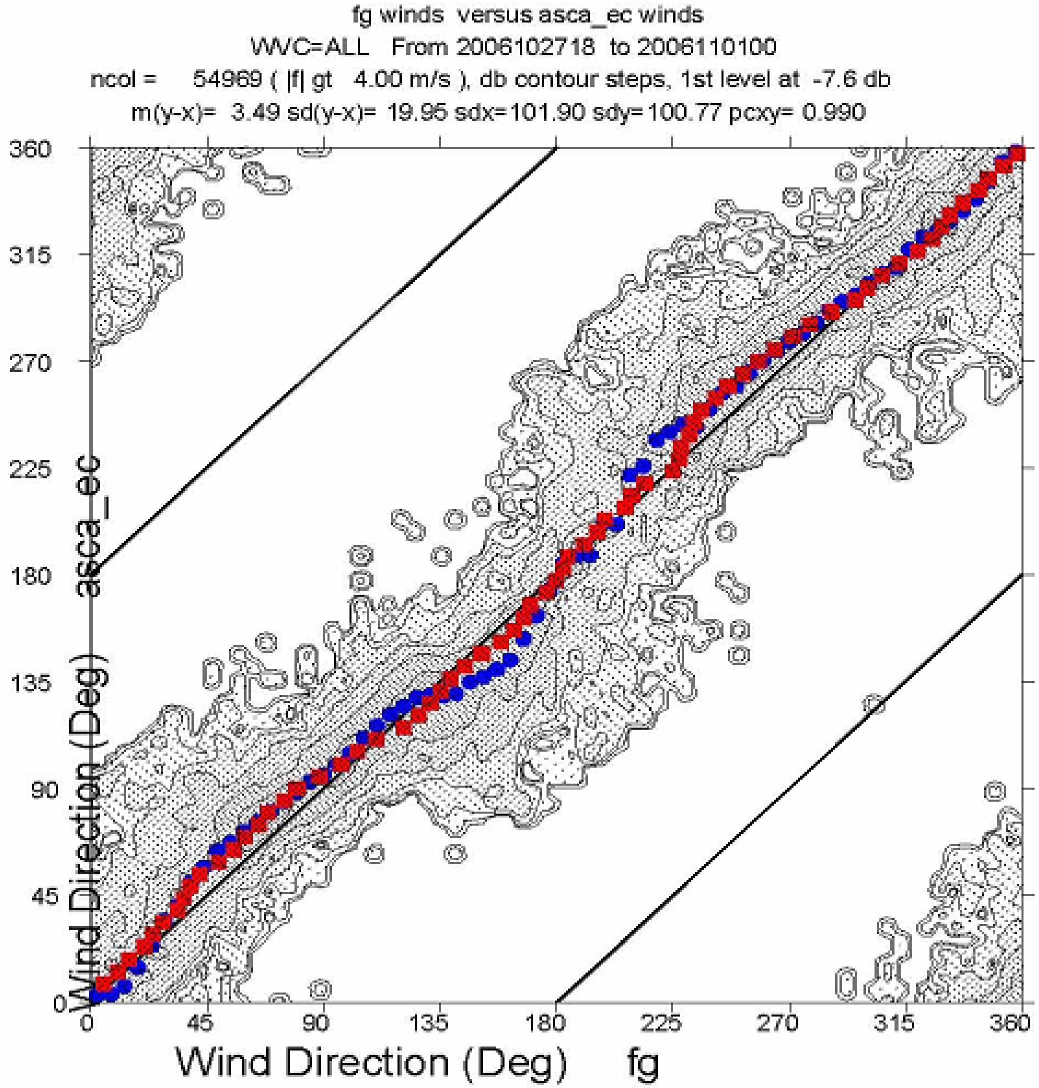
ASCAT

Normalised backscatter coefficients (σ_0)



ASCAT: first comparisons by ECMWF

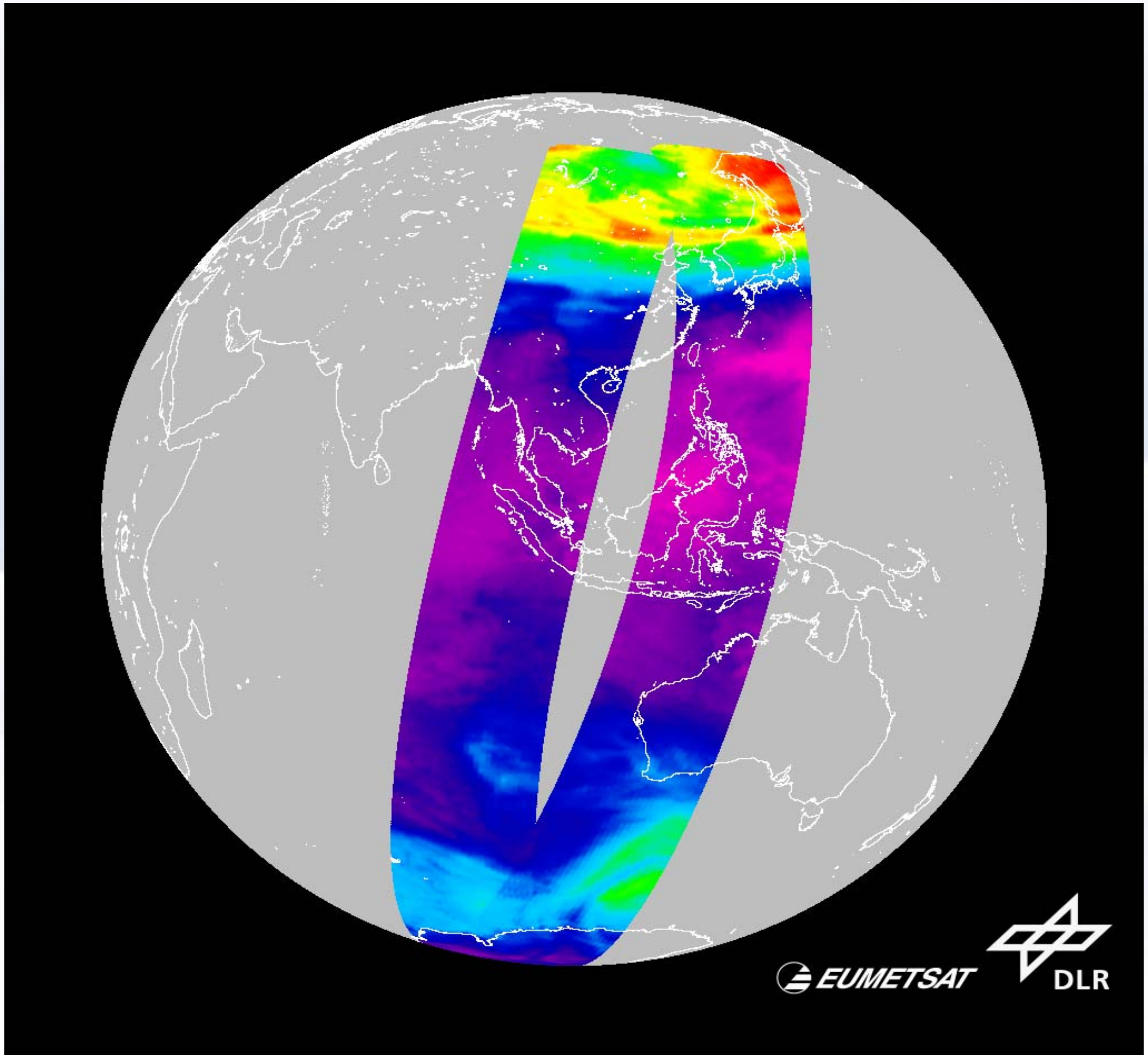




H. Hersbach, 2006

- GOME-2: Global Ozone Monitoring Experiment 2

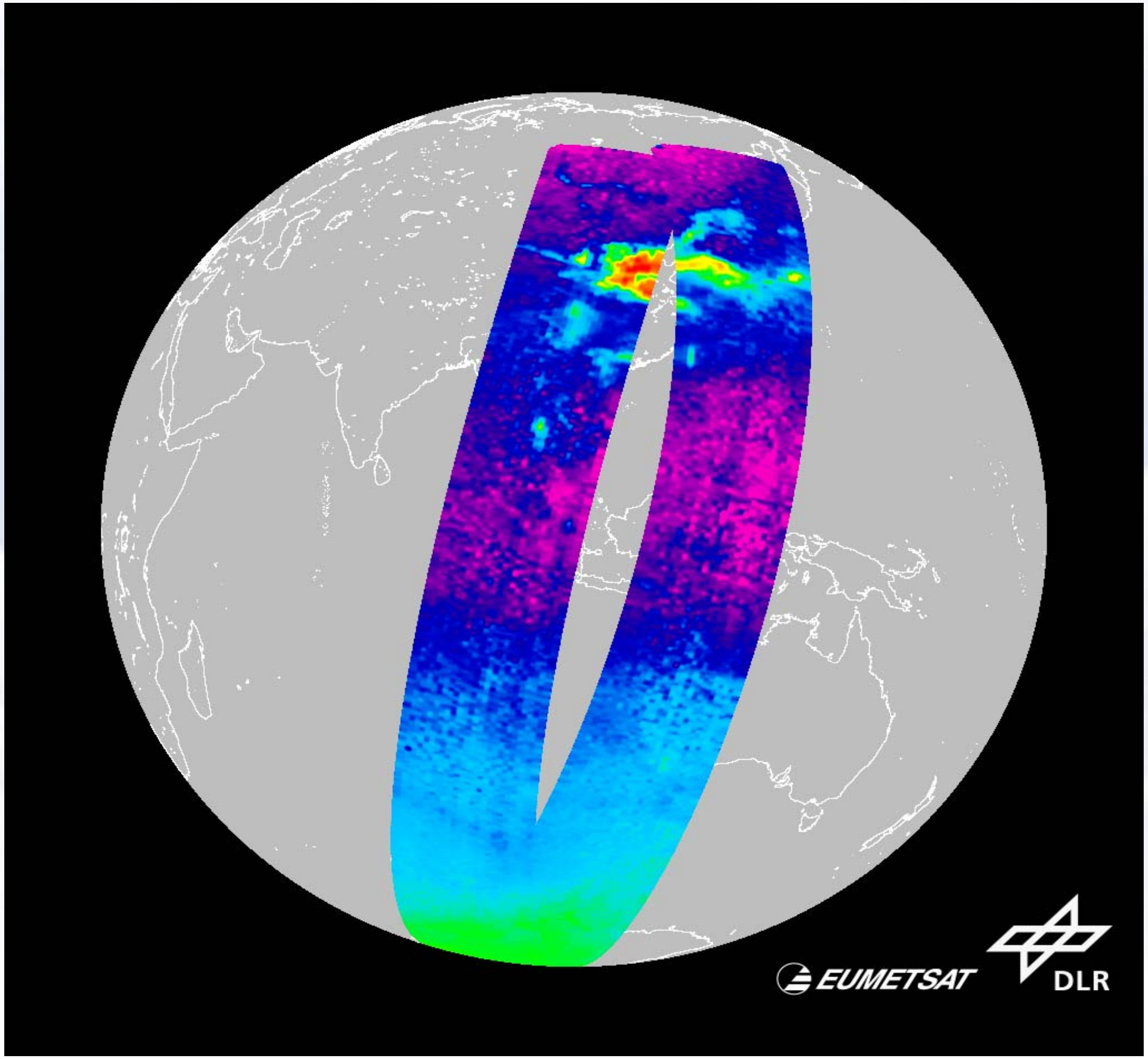
First GOME-2 ozone columnar contents



Ozone SAF Project

Loyola, 2007

First GOME-2 NO_2 columnar contents



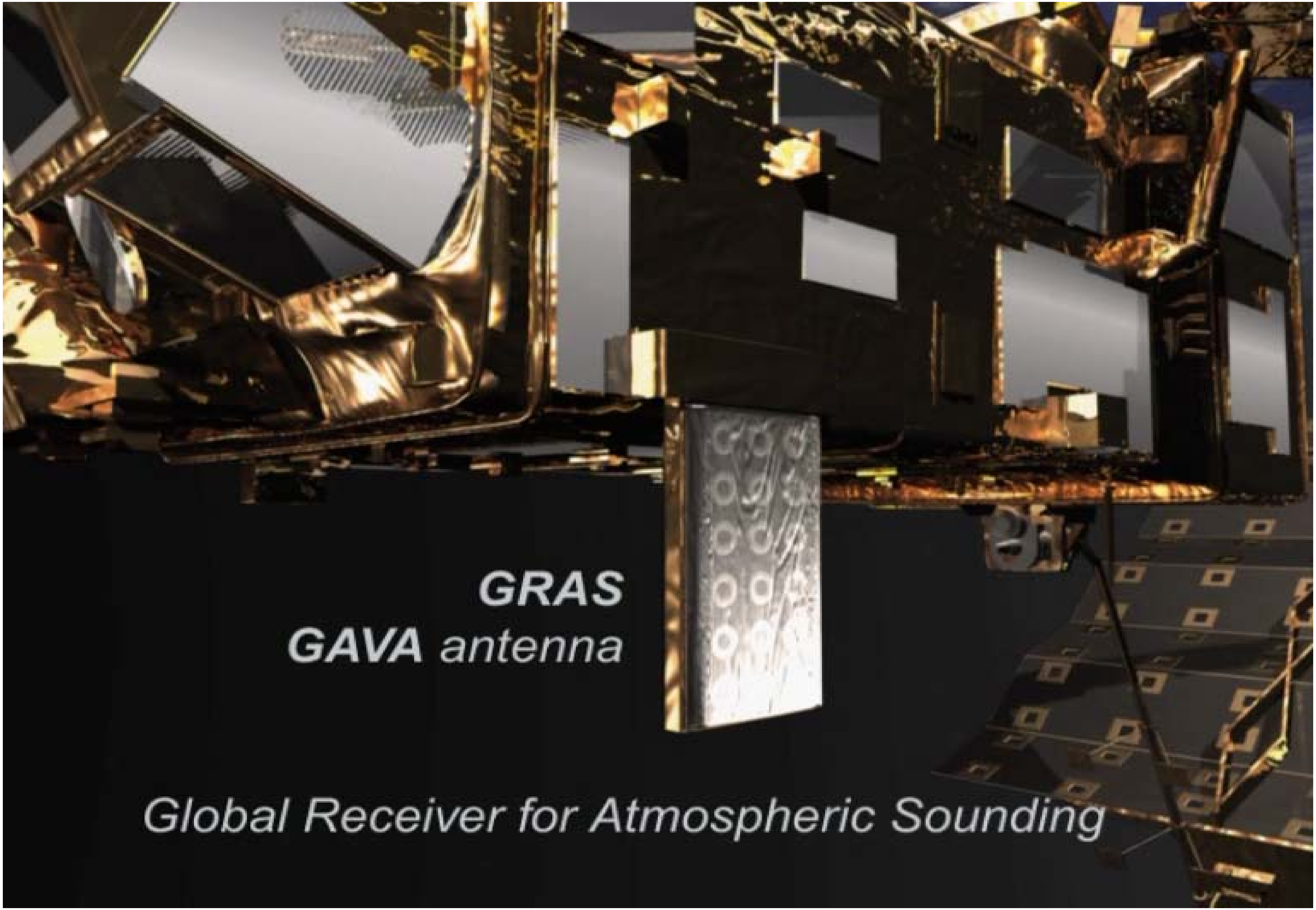
Ozone SAF Project

Loyola, 2007

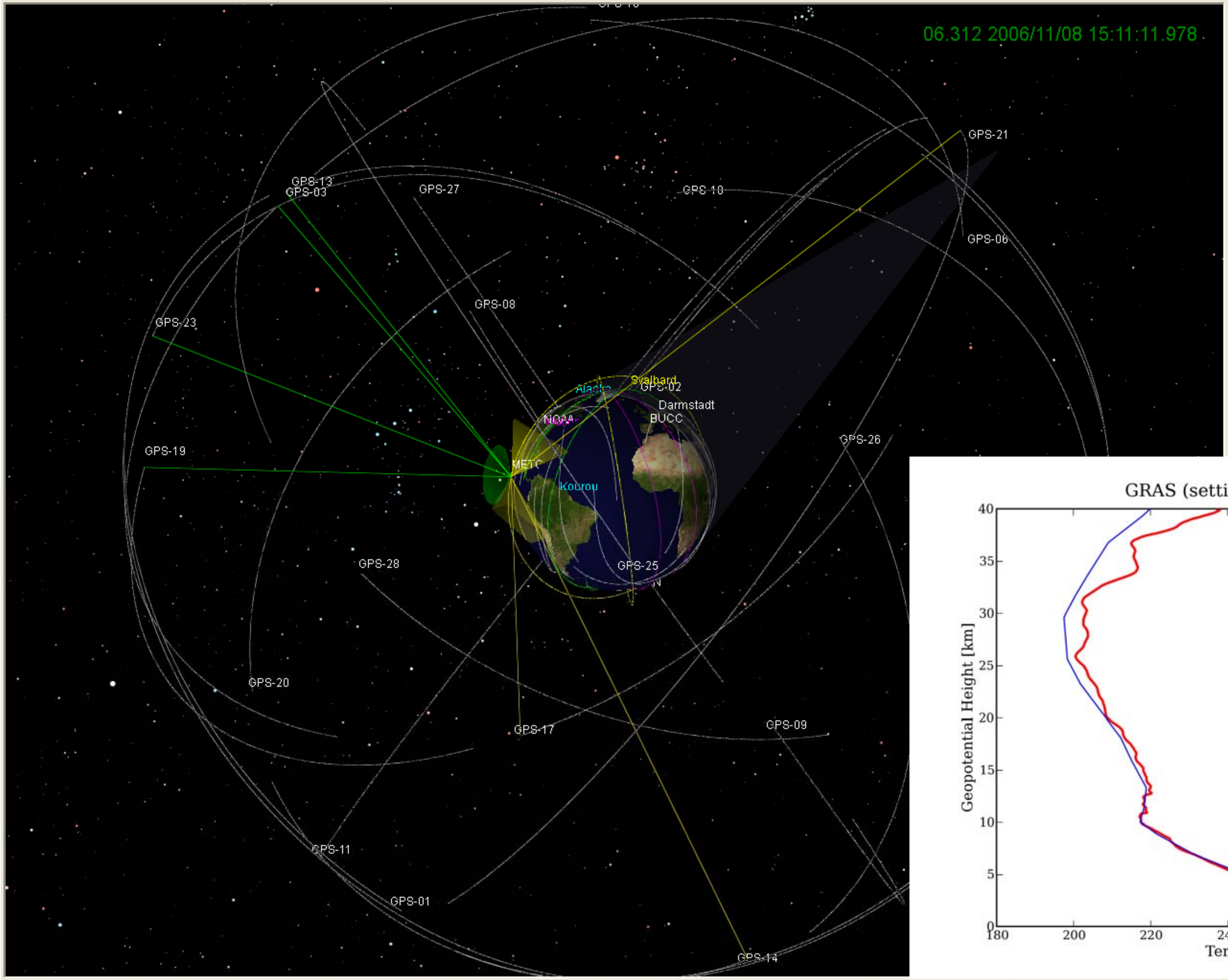
10^{16} mol cm^{-2}

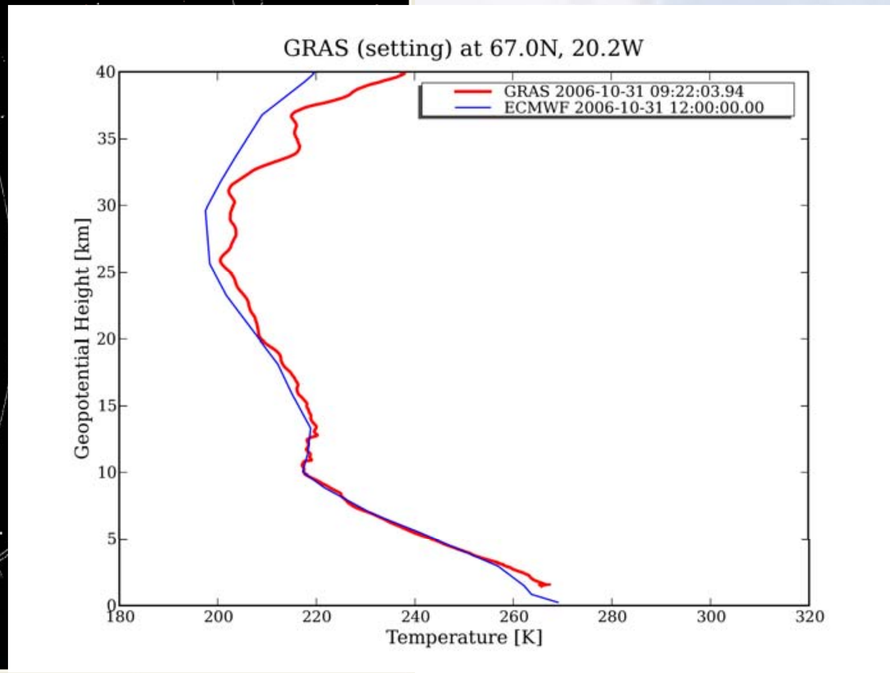
10^{15} mol cm^{-2}

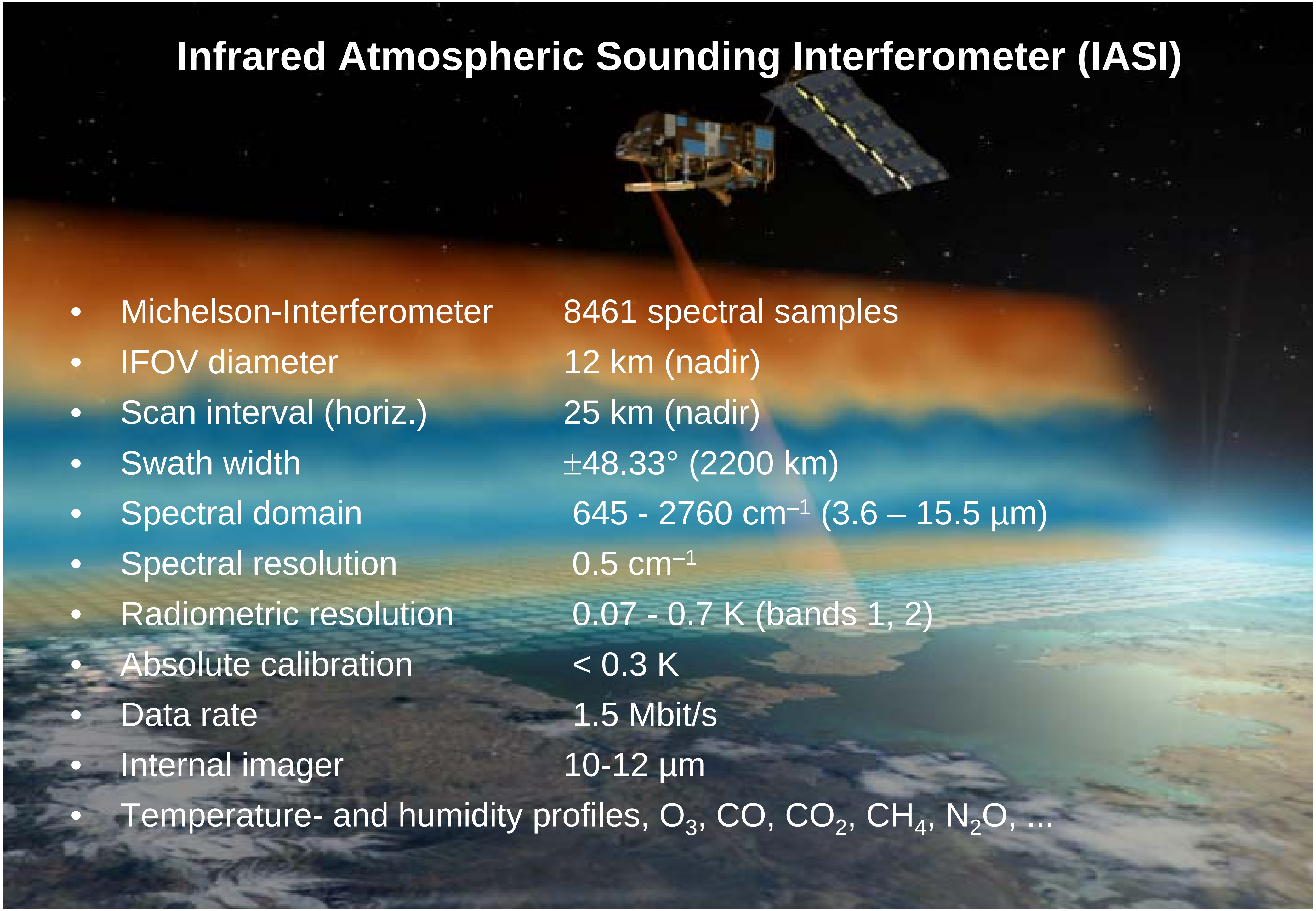
EUMETSAT

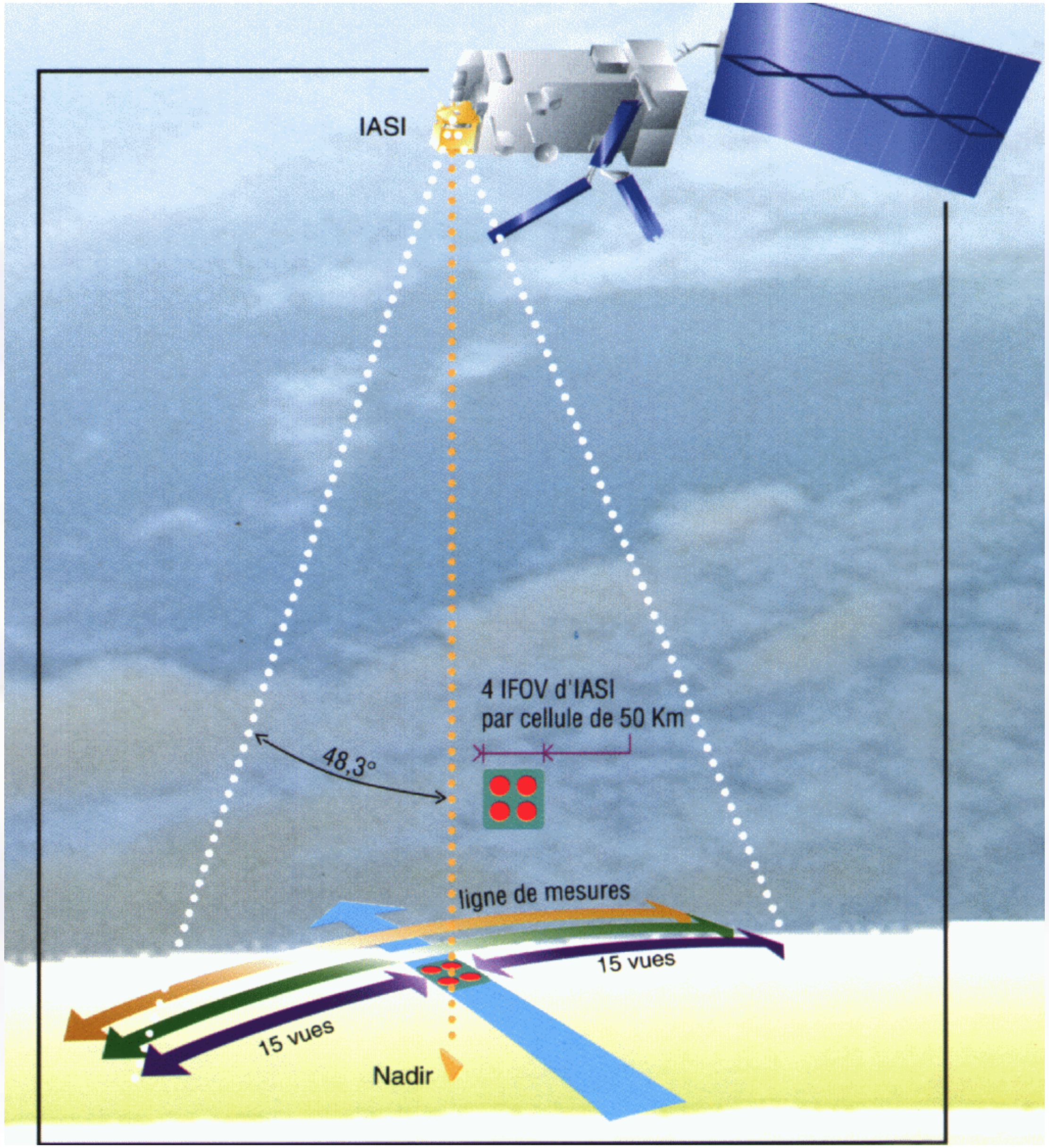

GRAS
GAVA antenna
Global Receiver for Atmospheric Sounding

GRAS:
Reception of GPS signals and its atmospheric diffraction

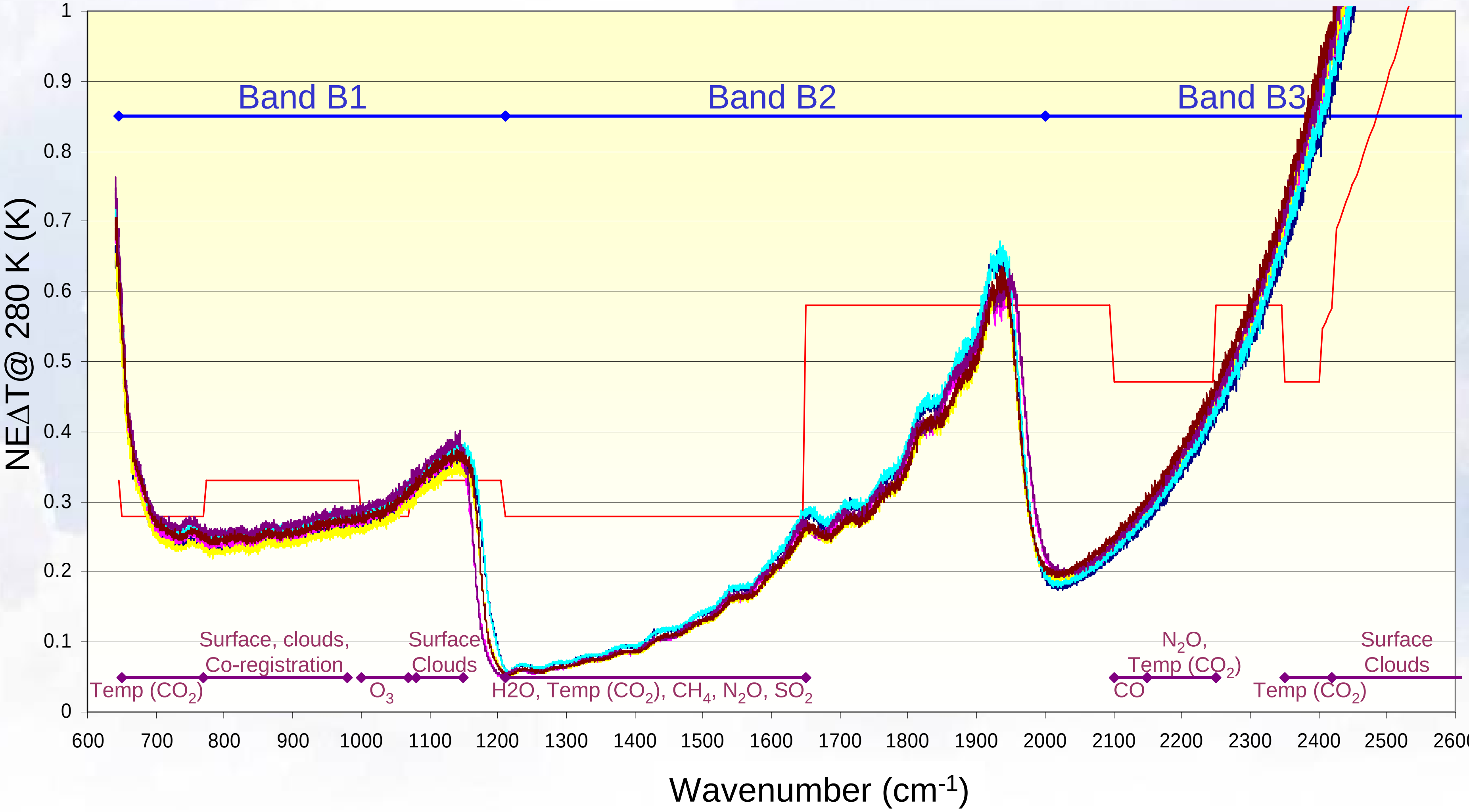




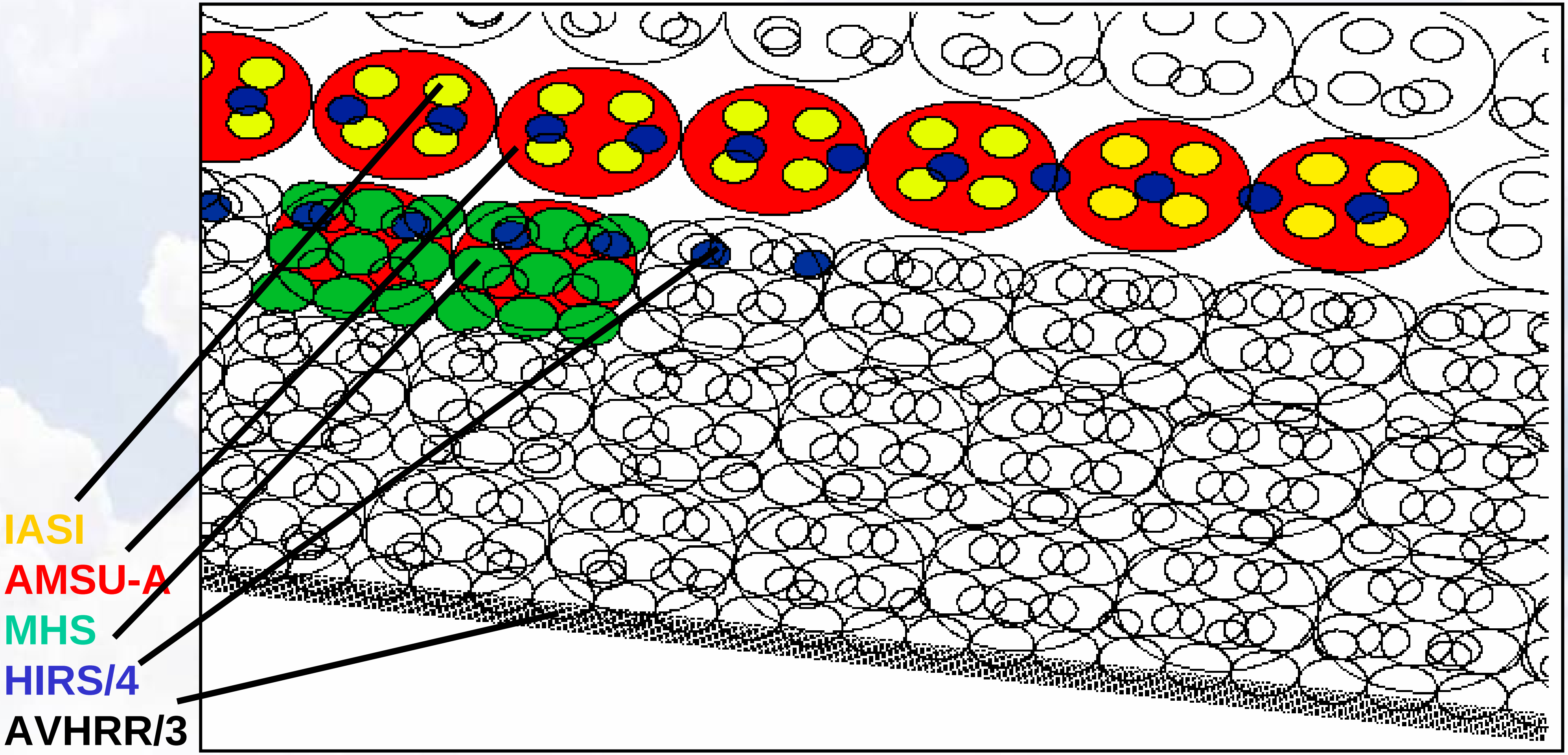

Infrared Atmospheric Sounding Interferometer (IASI)
• Michelson-Interferometer 8461 spectral samples
• IFOV diameter 12 km (nadir)
• Scan interval (horiz.) 25 km (nadir)
• Swath width ±48.33° (2200 km)
• Spectral domain 645 - 2760 cm^{-1} (3.6 – 15.5 µm)
• Spectral resolution 0.5 cm^{-1}
• Radiometric resolution 0.07 - 0.7 K (bands 1, 2)
• Absolute calibration < 0.3 K
• Data rate 1.5 Mbit/s
• Internal imager 10-12 µm
• Temperature- and humidity profiles, O_3, CO, CO_2, CH_4, N_2O, ...


IASI
4 IFOV d'IASI
par cellule de 50 Km
48,3°
ligne de mesures
15 vues
15 vues
Nadir

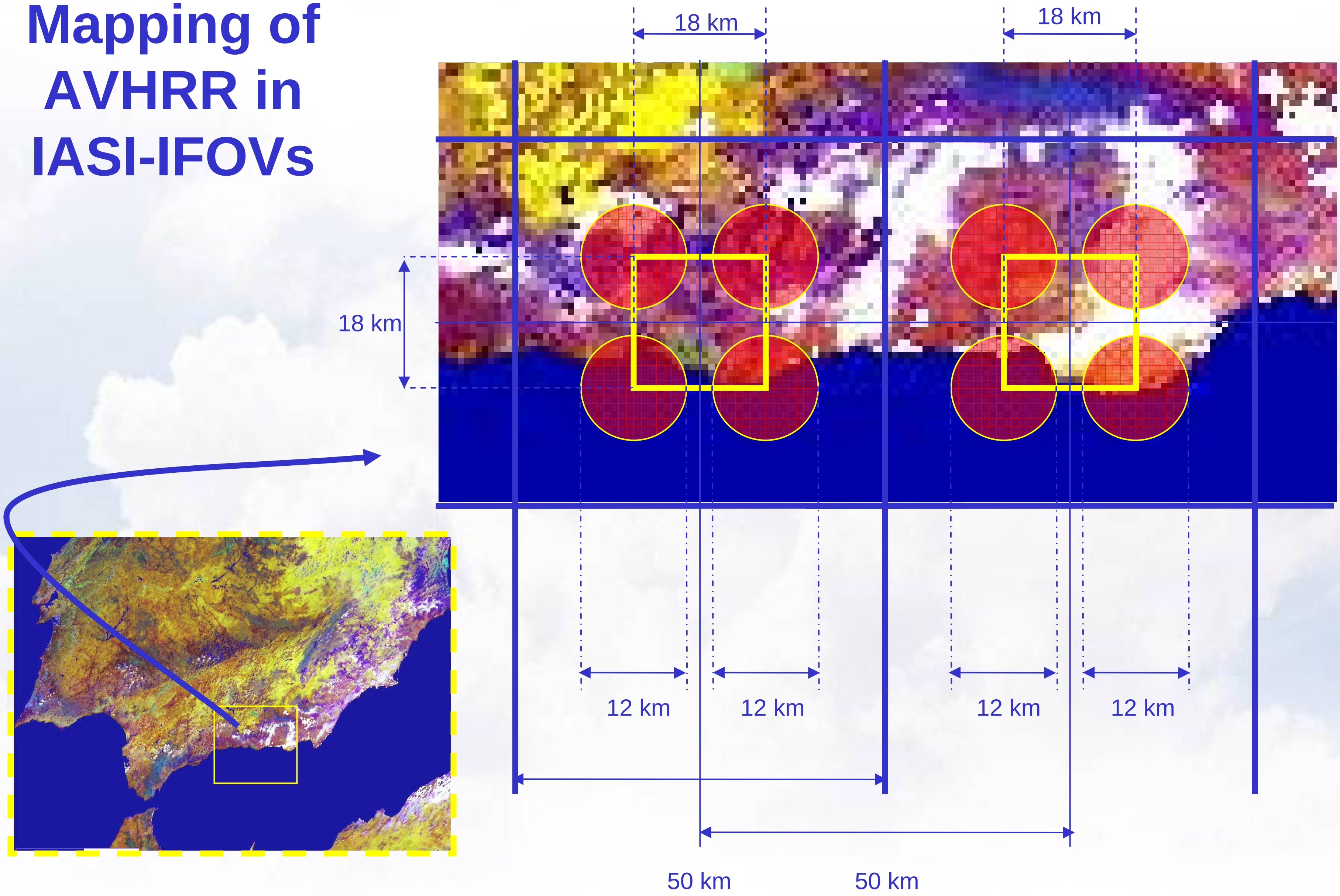
IASI FM-2: Radiometric noise



Scan patterns of the instruments



Mapping of AVHRR in IASI-IFOVs



IASI Level 2 product generation

IASI Level 1c | **AVHRR Cloud Mask and S/CTT** | **Configurable Databases**

ATOVS Level 2 | **AMSU-A Level 1** | **MHS Level 1** | **NWP Forecast**

Pre-Processing

Cloud Processing

Geophysical Parameters Retrieval

Monitoring Information | **Level 2 Product** | **Quality Information**

Properties of the Operational IASI L2 Processor (1/3)

- For a best use of IASI measurements the level 2 processing can combine IASI with concurrent measurements of AVHRR, AMSU-A, MHS, and ATOVS Level 2 products
- IASI stand-alone processing is possible if other measurements are not available, or if Product Processing Facility is explicitly configured to exclude other instruments
- NWP forecast is included to provide surface pressure as reference for the profiles to be retrieved and surface wind speed over sea for the calculation of surface emissivity
- Optionally, the NWP forecast profiles of temperature, water vapour and ozone can be used to initialise and/or constrain the retrieval

Properties of the Operational IASI L2 Processor (2/3)

- Processing is steered by configuration settings (80 configurable auxiliary data sets), which allows for optimisation of Product Processing Facility before and during commissioning
- Online quality control supports the choice of best processing options in case of partly unavailable IASI data or corrupt side information (data from other instruments or NWP forecast)
- Besides error covariances a number of flags are generated steering through the processing and giving quality indicators; 40 flags are specified, which are part of the product

Properties of the operational IASI L2 Processor (3/3)

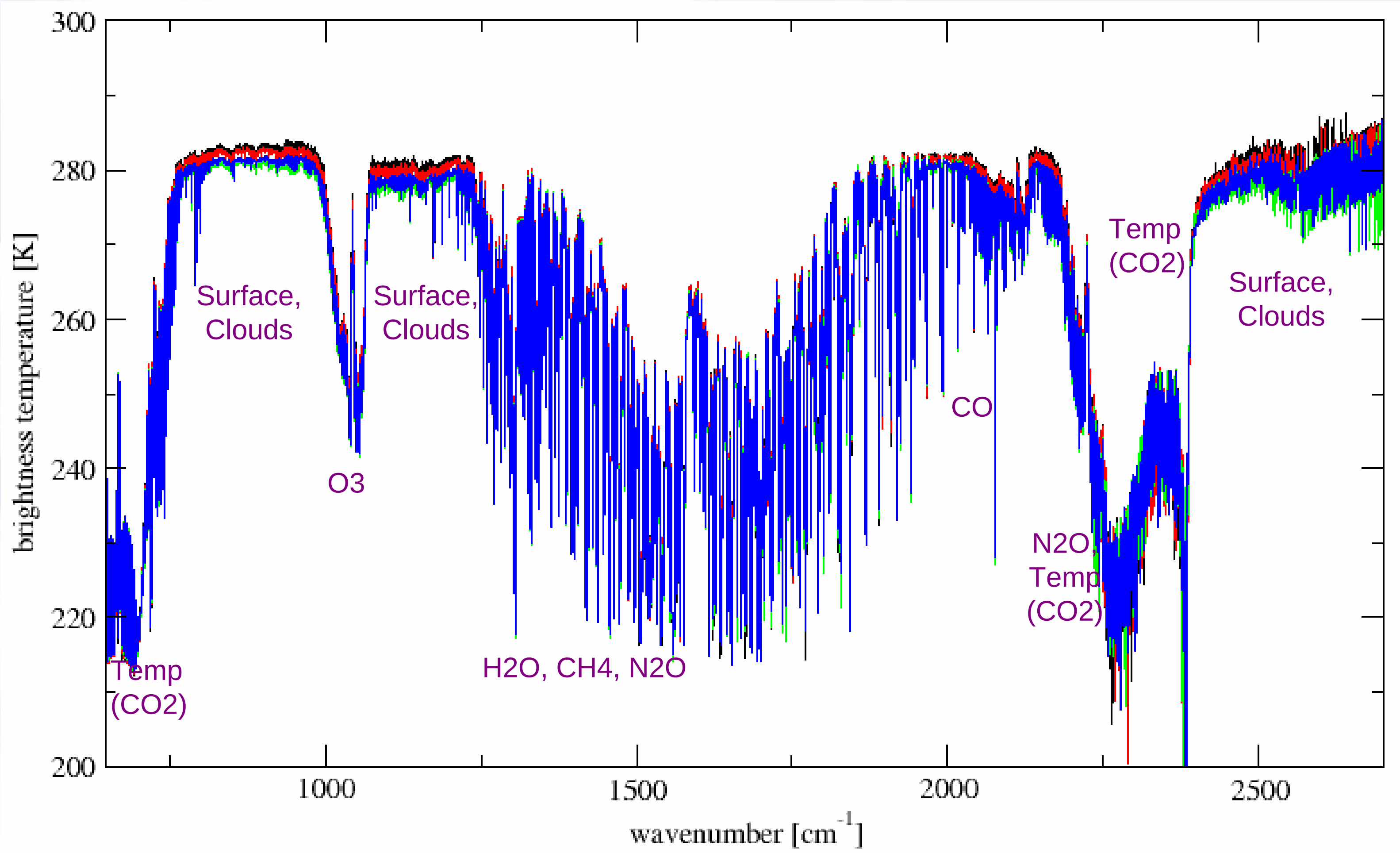
- All 8461 IASI spectral samples, covering the spectral region from 645 to 2760 cm^{-1}, are used in the retrieval to maximise the retrieved information
- The Product Processing Facility supports nominal and degraded instrument modes (e.g. failure of single detectors/bands)
- Bias control by radiance tuning via configuration

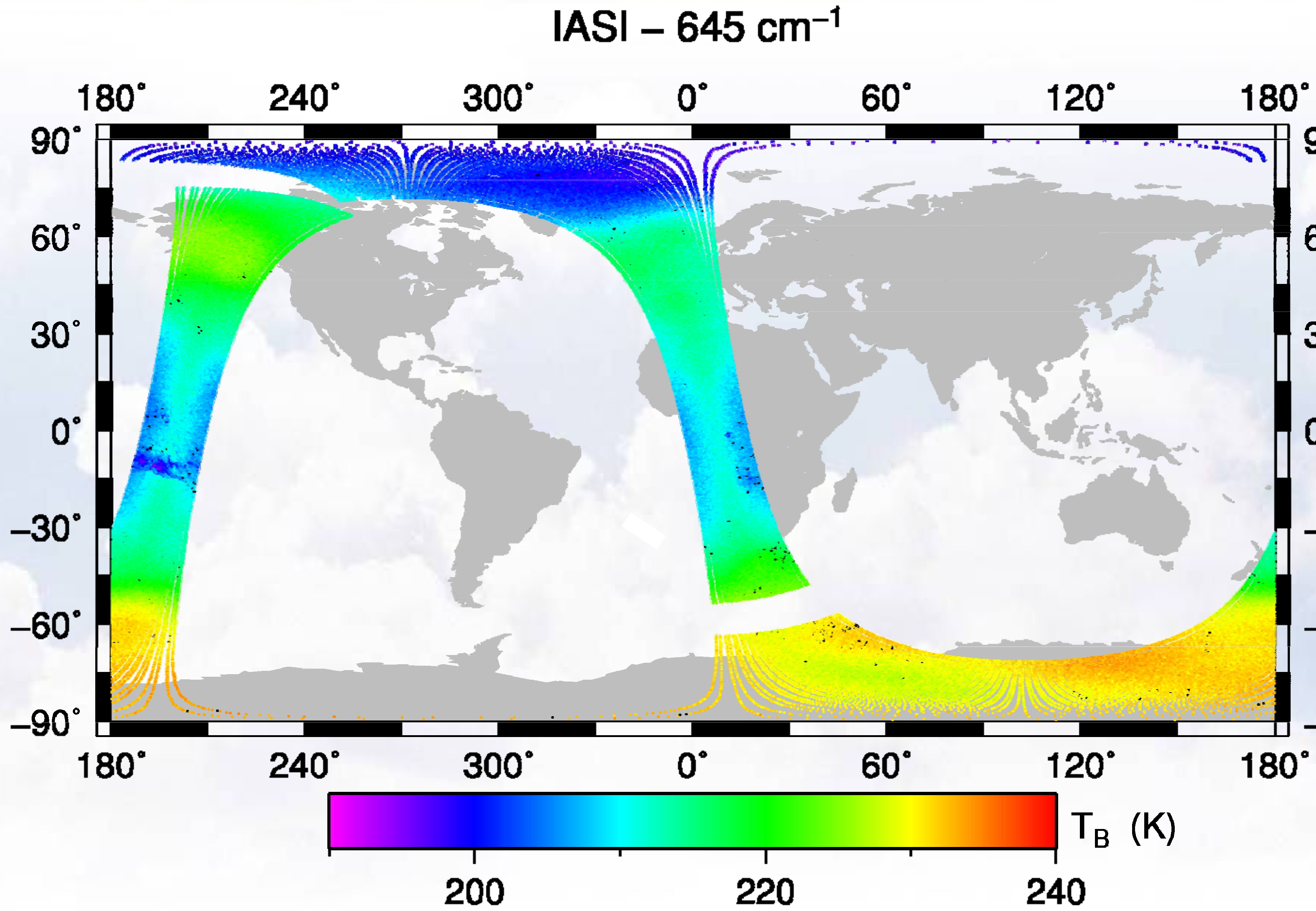
Cloud processing

- Cloud detection
  - AVHRR-based cloud detection using Scenes Analysis from AVHRR Level 1 processing
  - Combined IASI / ATOVS cloud detection
  - IASI stand-alone cloud detection

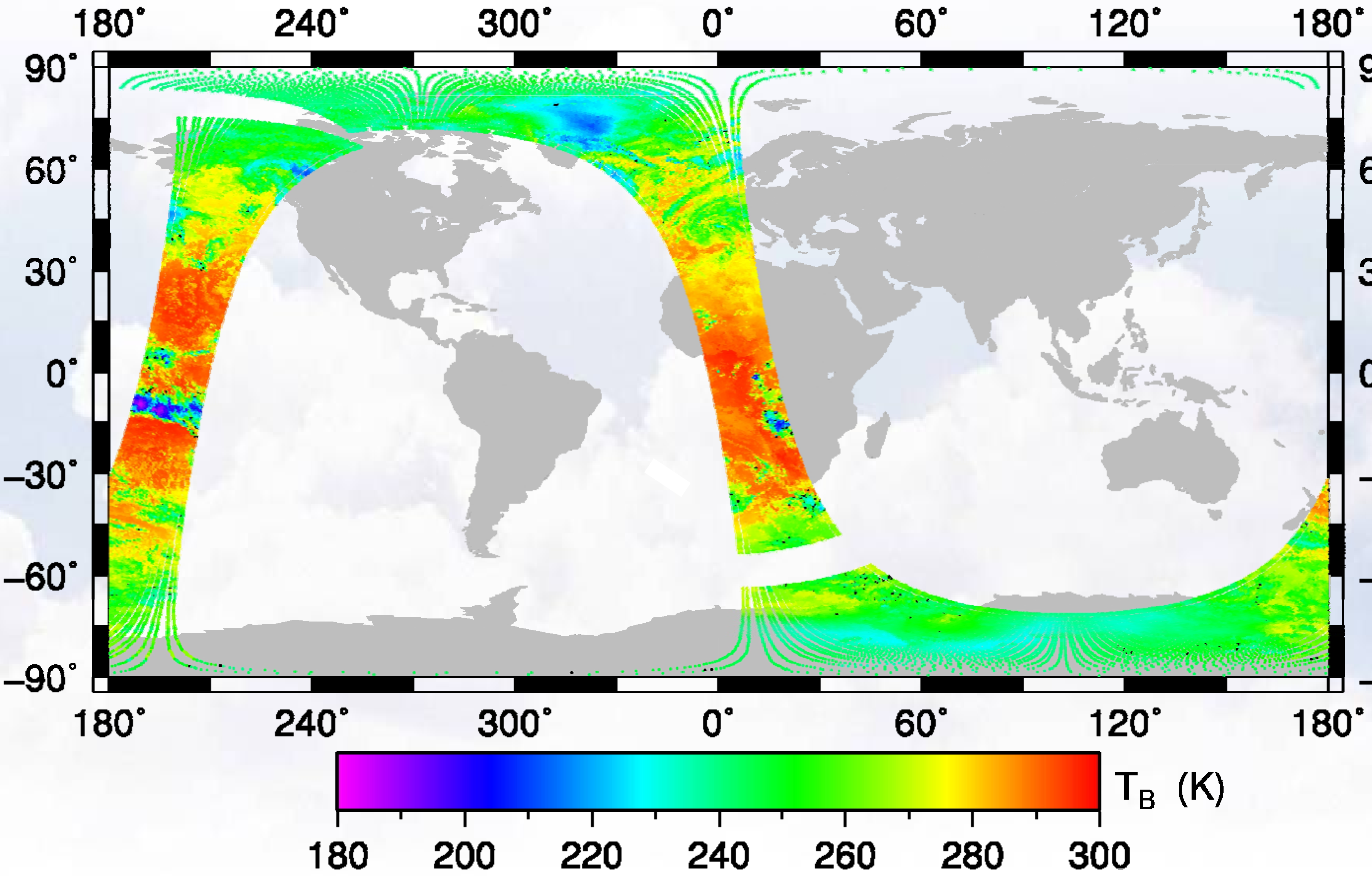
- Cloud parameters retrieval
  - Cloud fraction
  - Cloud top height
  - Cloud phase

First IASI spectra on 29 November 2006



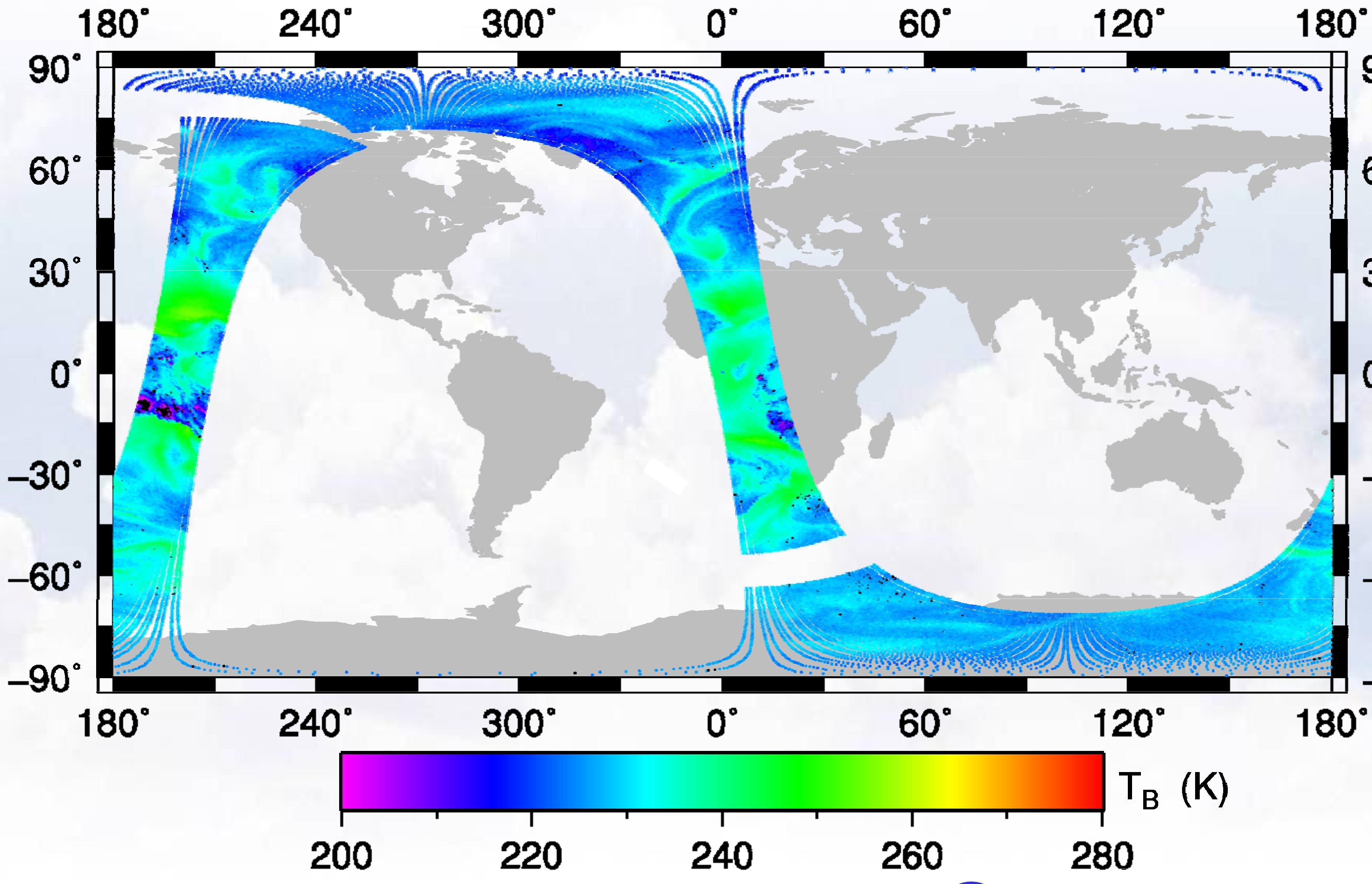

IASI – 645 cm⁻¹
180° 240° 300° 0° 60° 120° 180°
90° 60° 30° 0° –30° –60° –90°
T_B (K)
200 220 240

IASI – 945 cm^{-1}



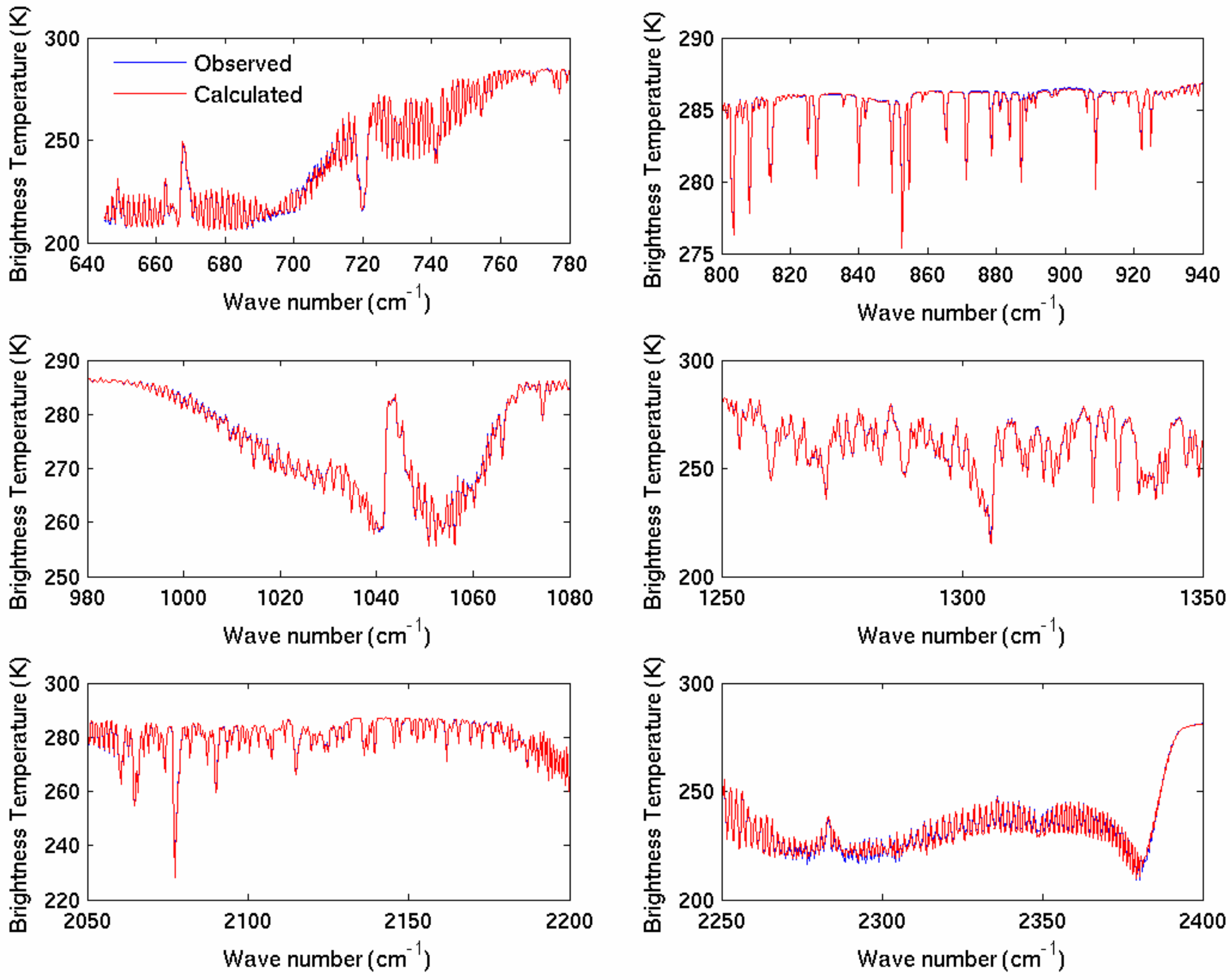
EUMETSAT

IASI – 1645 cm^{-1}

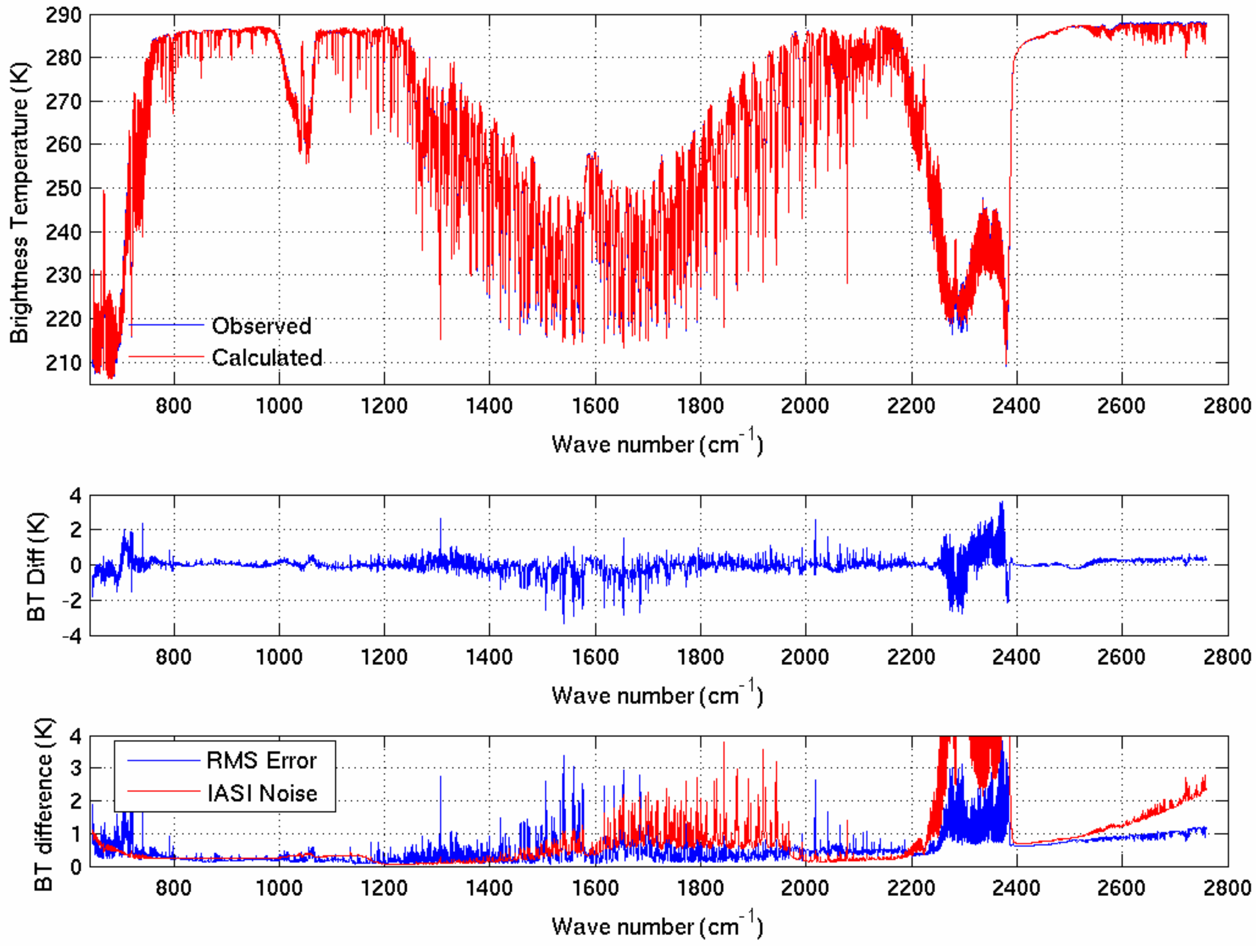


EUMETSAT

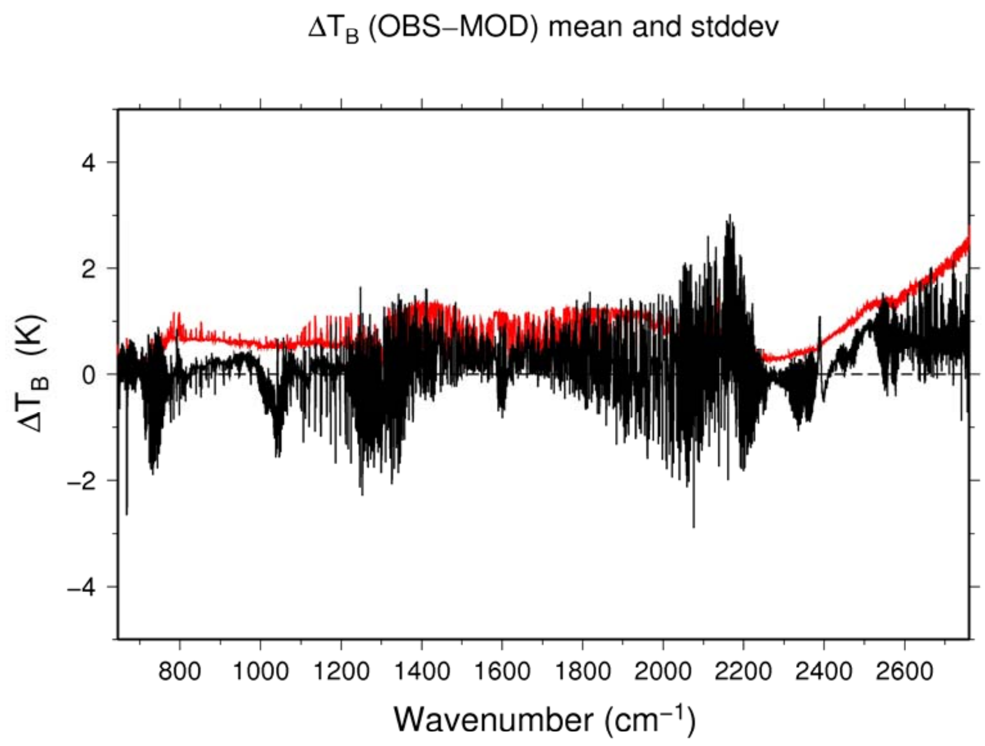
Comparisons of simulated and measured spectra



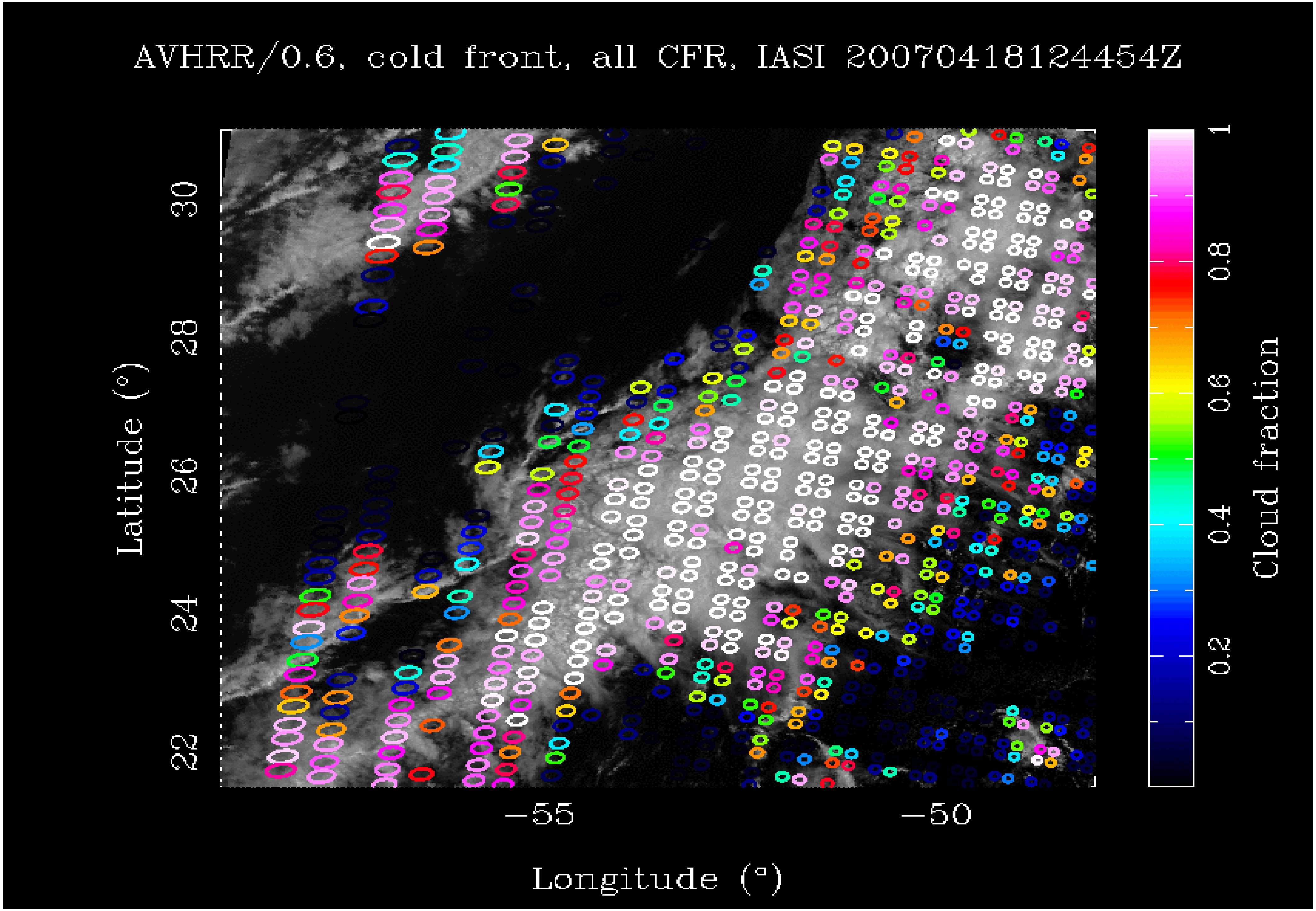
Comparisons of simulated and measured spectra



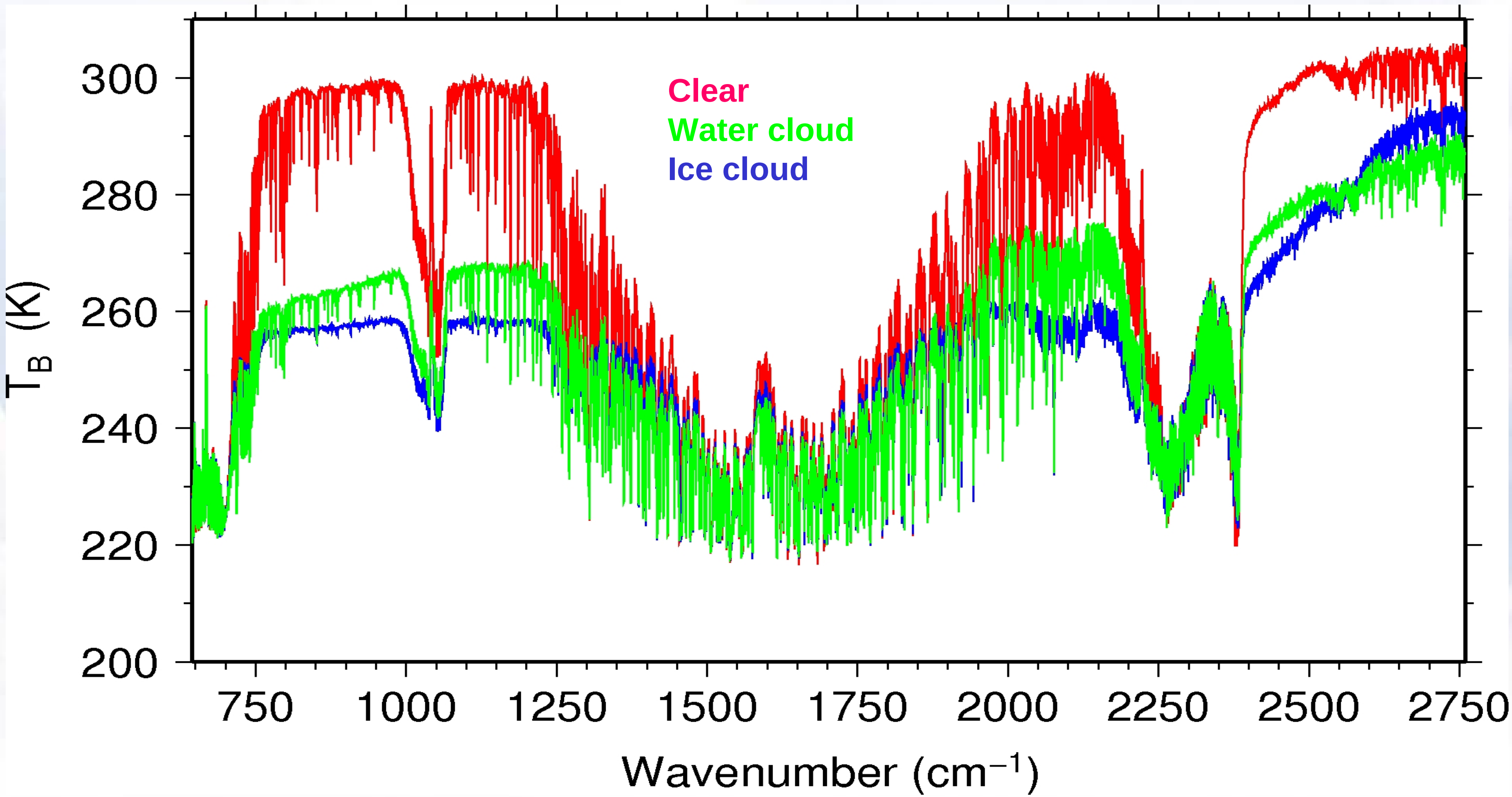
Correction of systematic errors



- All retrieval and assimilation schemes use radiative transfer calculations as basis
- Prerequisite for the functionality of the retrieval or assimilation is a good representativity of the measurements by simulated radiances
- Systematic errors:
  - Approxmations necessary for fast calculations
  - Insufficient knowledge of spectroscopic data
  - Erroneous input data
- Systematic fit of models to IASI measurements


AVHRR/0.6, cold front, all CFR, IASI 20070418124454Z
30
28
26
24
22
Latitude (°)
−55
−50
Longitude (°)
1
0.8
0.6
0.4
0.2
Cloud fraction

Discrimination of ice and water clouds



Geophysical parameters retrieval: state vector to be retrieved

- The state vector to be retrieved consists of the following parameters
  - Temperature profile at a minimum of 40 levels
  - Water vapour profile at a minimum of 20 levels
  - Ozone columns in deep layers (0-6km, 0-12 km, 0-16 km, total column)
  - Land or sea surface temperature
  - Surface emissivity at 12 spectral positions
  - Columnar amounts of N_2O, CO, CH_4, CO_2
  - Cloud amount (up to three cloud formations)
  - Cloud top temperature (up to three cloud formations)
  - Cloud phase

- In case of clouds and elevated surface the state vector has to be modified

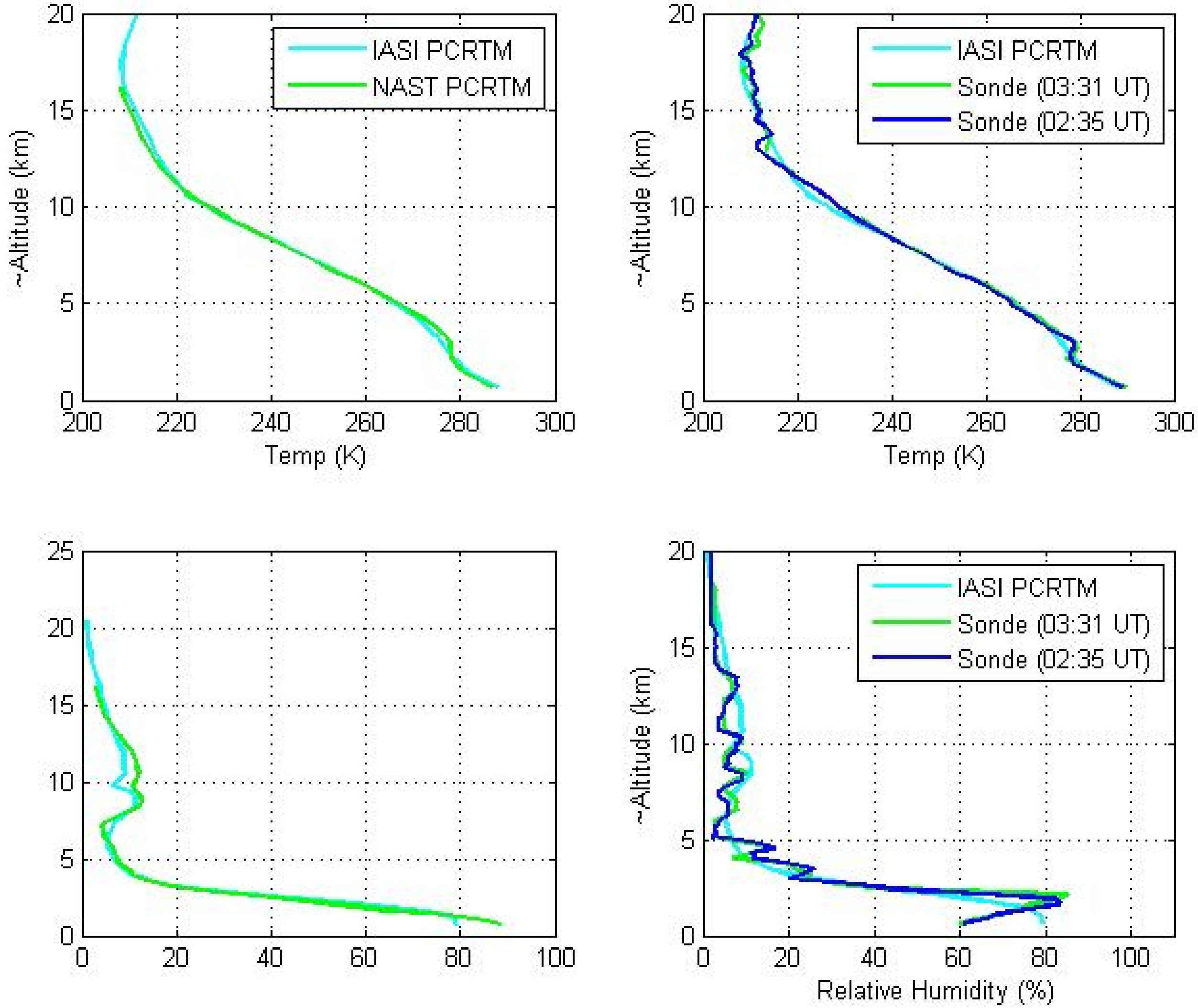
Geophysical parameters retrieval: first retrieval

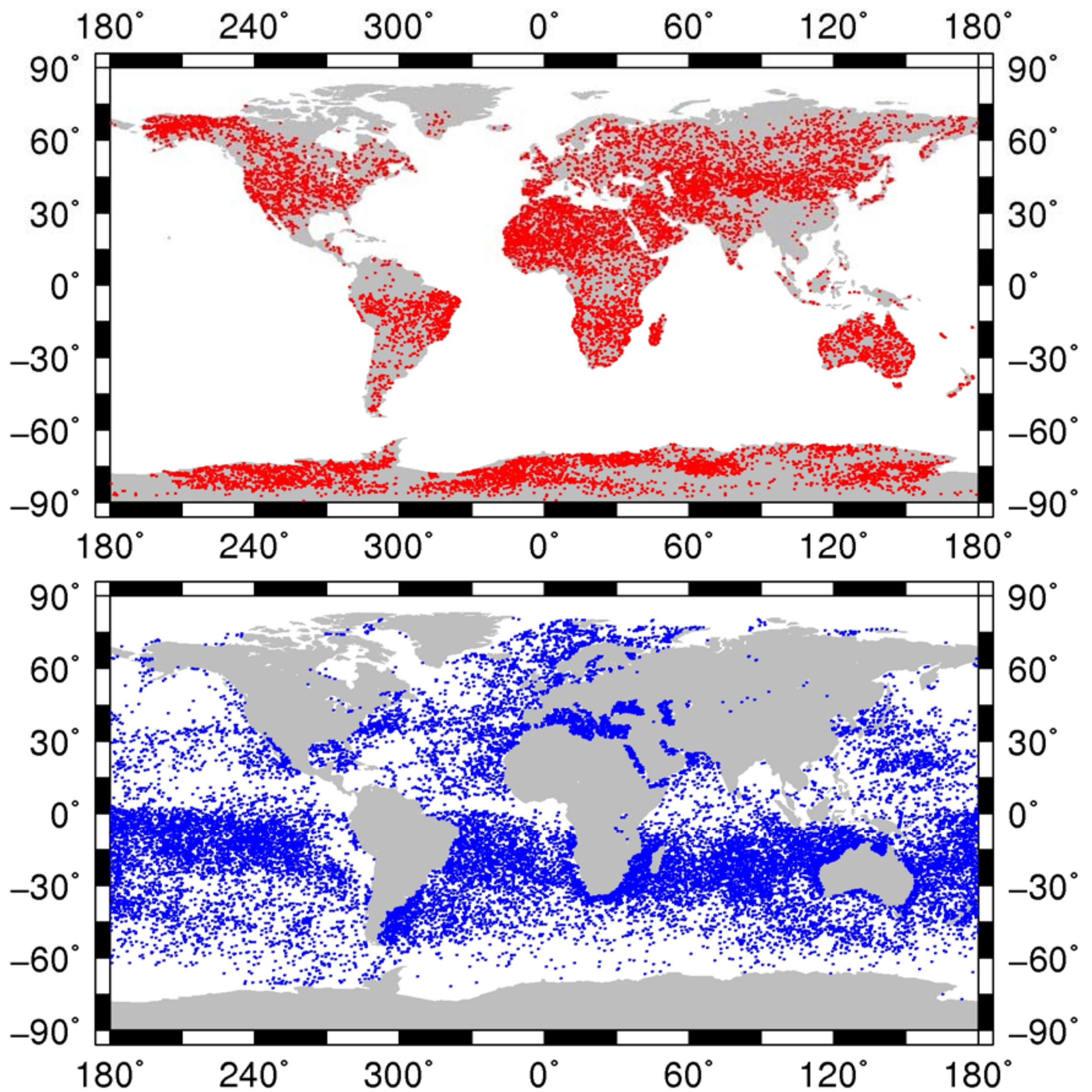
- Spectra PC scores regression for temperature and water-vapour, and ozone profiles, surface temperature, and surface emissivity
- Artificial neural network (multi-layer perceptron) for trace gases (optionally also for temperature, water-vapour and ozone, depends on configuration setting)
- The results from the first retrieval may constitute the final product or may serve as input to the final, iterative retrieval; the choice depends on configuration setting and on quality of the first retrieval results

Geophysical paramters retrieval: final, iterative retrieval

- Simultaneous iterative retrieval, seeking maximum probability solution for minimisation of cost function by Marquardt-Levenberg method, using a subset of IASI channels, single or combined to super-channels
- Initialisation with results from first retrieval
- Other choices of initialisation may be selected, depending on configuration setting and availability (e.g. NWP forecast, climatology, ATOVS Level 2 product)
- Background state vector from climatology, ATOVS Level 2 product, adjacent retrieval, or NWP forecast, depending on configuration and availability
- State vector to be iterated depends on cloud conditions and configuration setting (clear, cloudy, variational cloud clearing)

Comparison: IASI / NAST-I / radiosonde





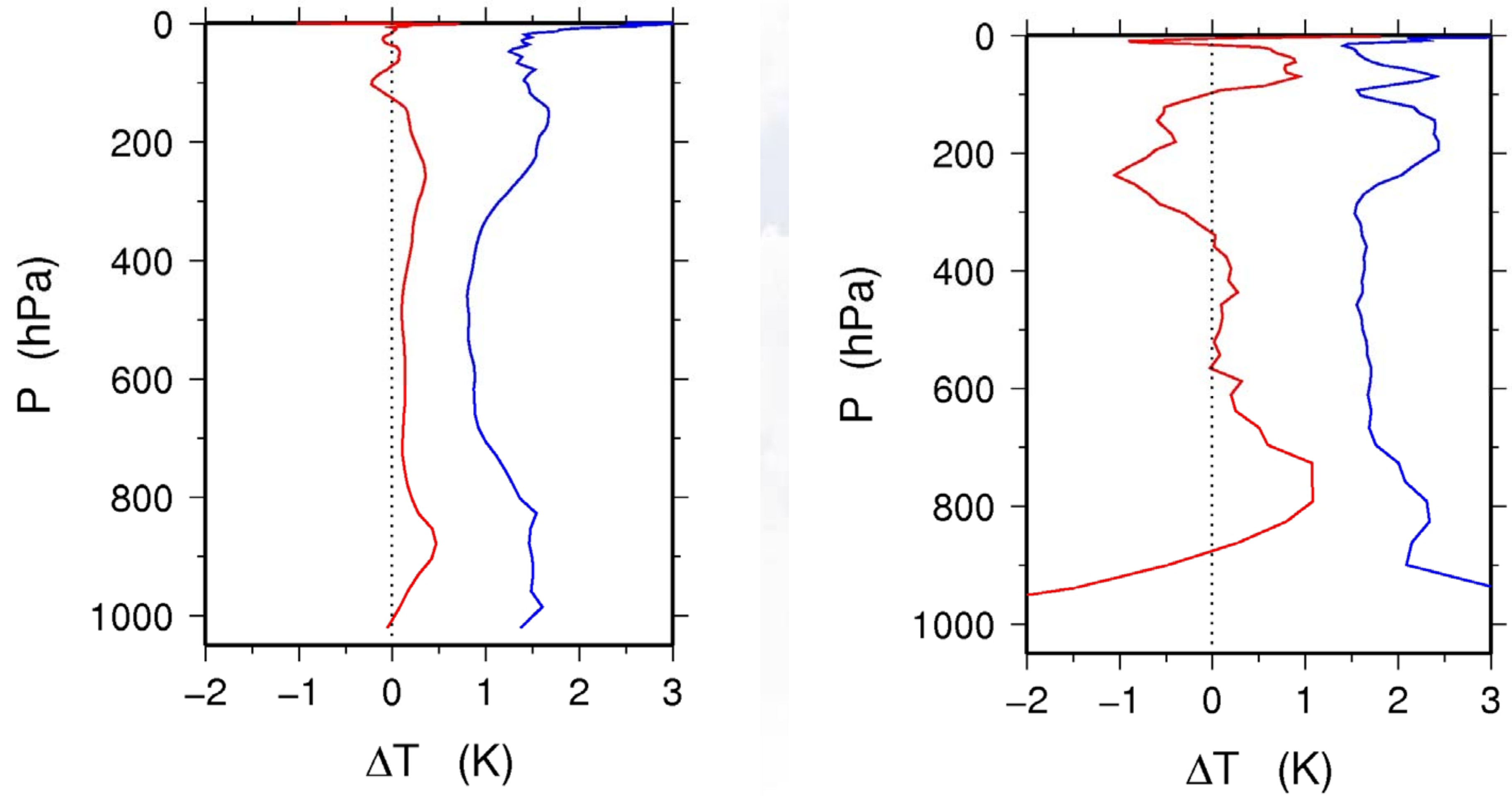
Comparison: ECMWF / IASI

Clear situations
May – June 2007

Land: 1330 match-ups

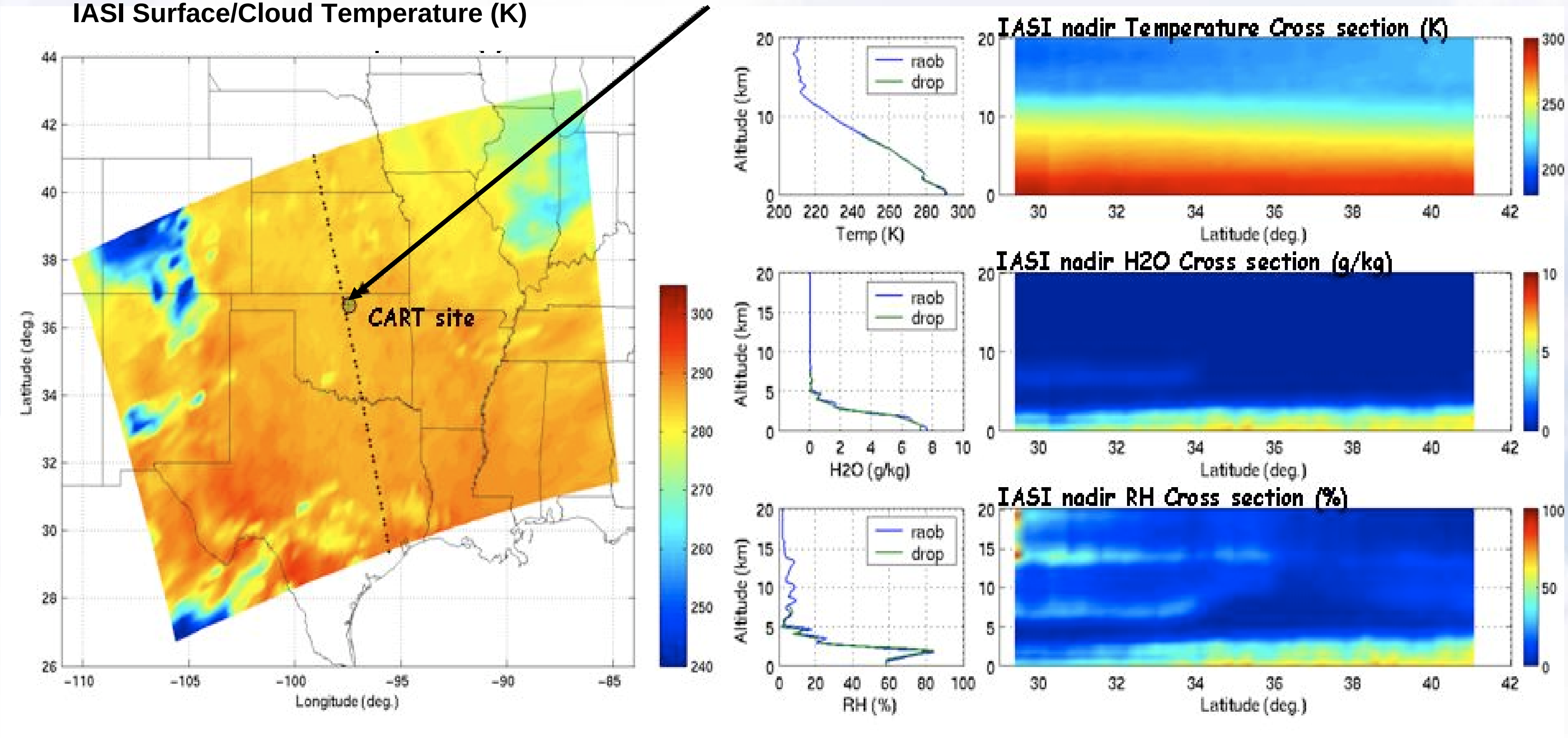
Ocean: 21810 match-ups

Comparison: ECMWF – IASI L2

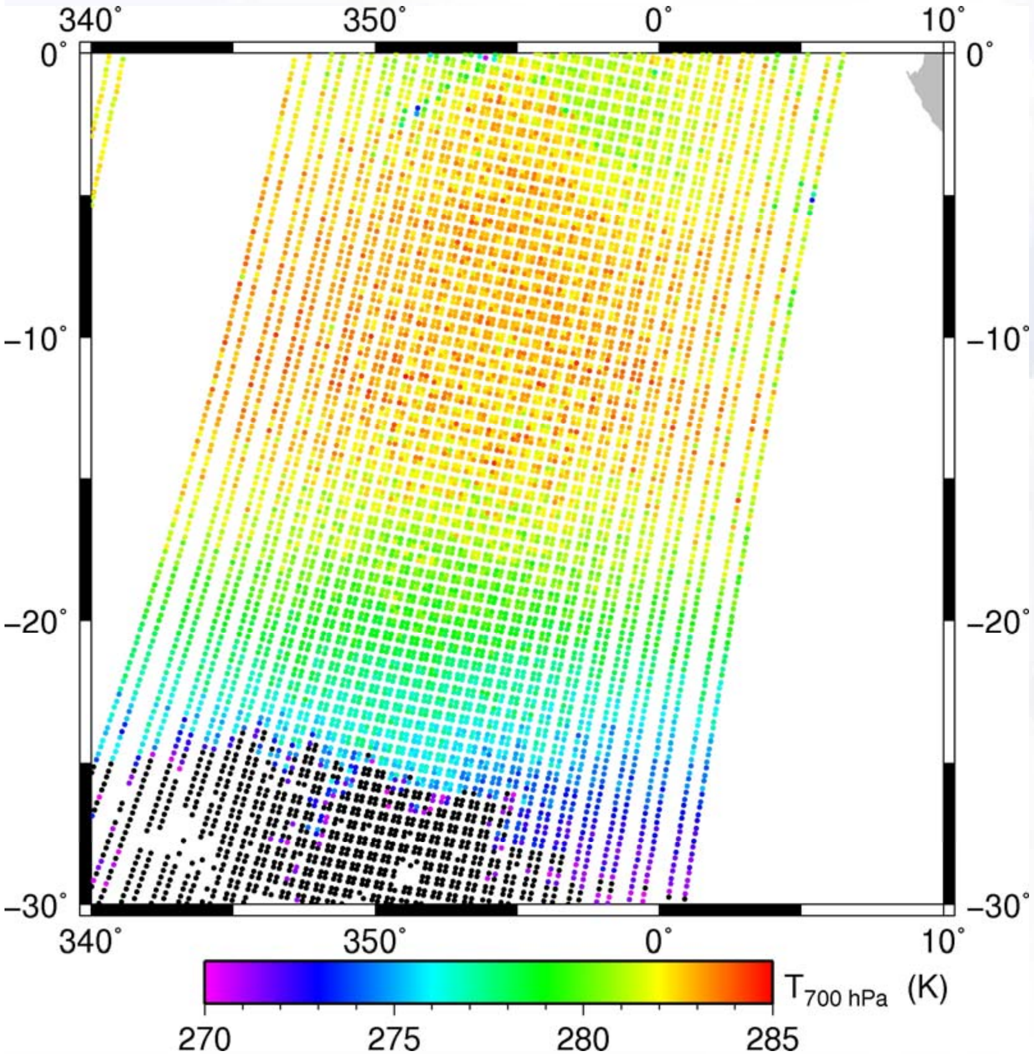


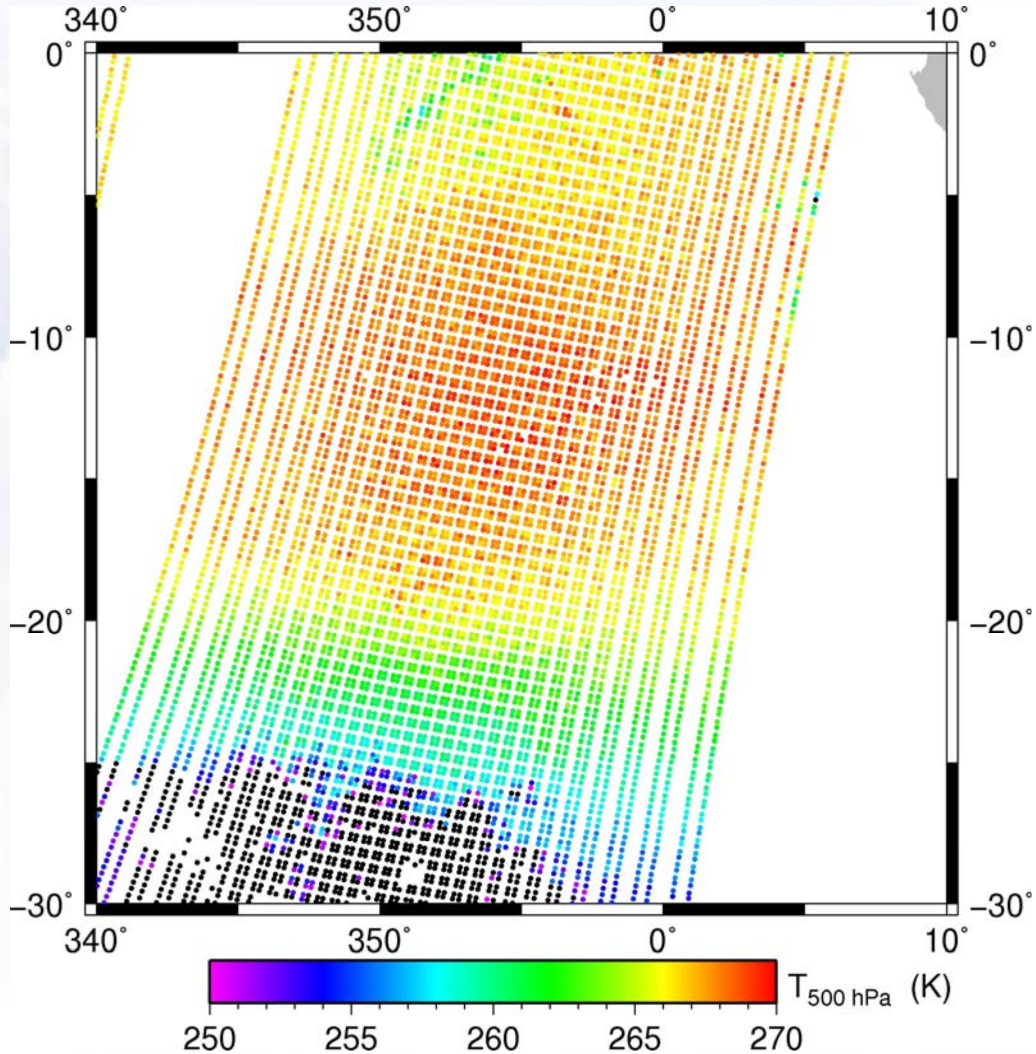
JAIVEx: Joint Airborne IASI Validation Experiment

Oklahoma ARM-CART Site Used for IASI Validation

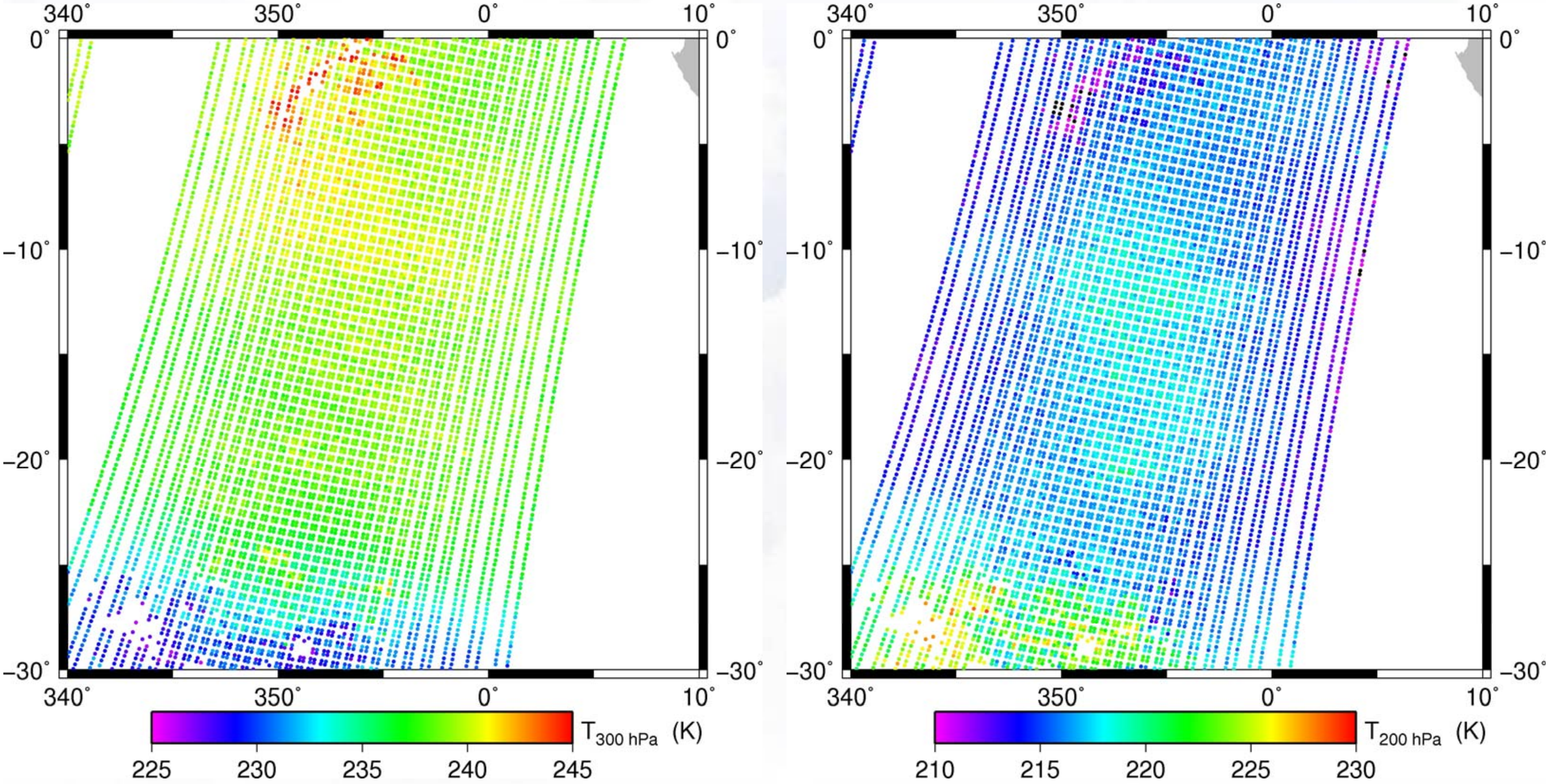


IASI: temperature retrievals on 10 June 2007 ~09:30 UTC

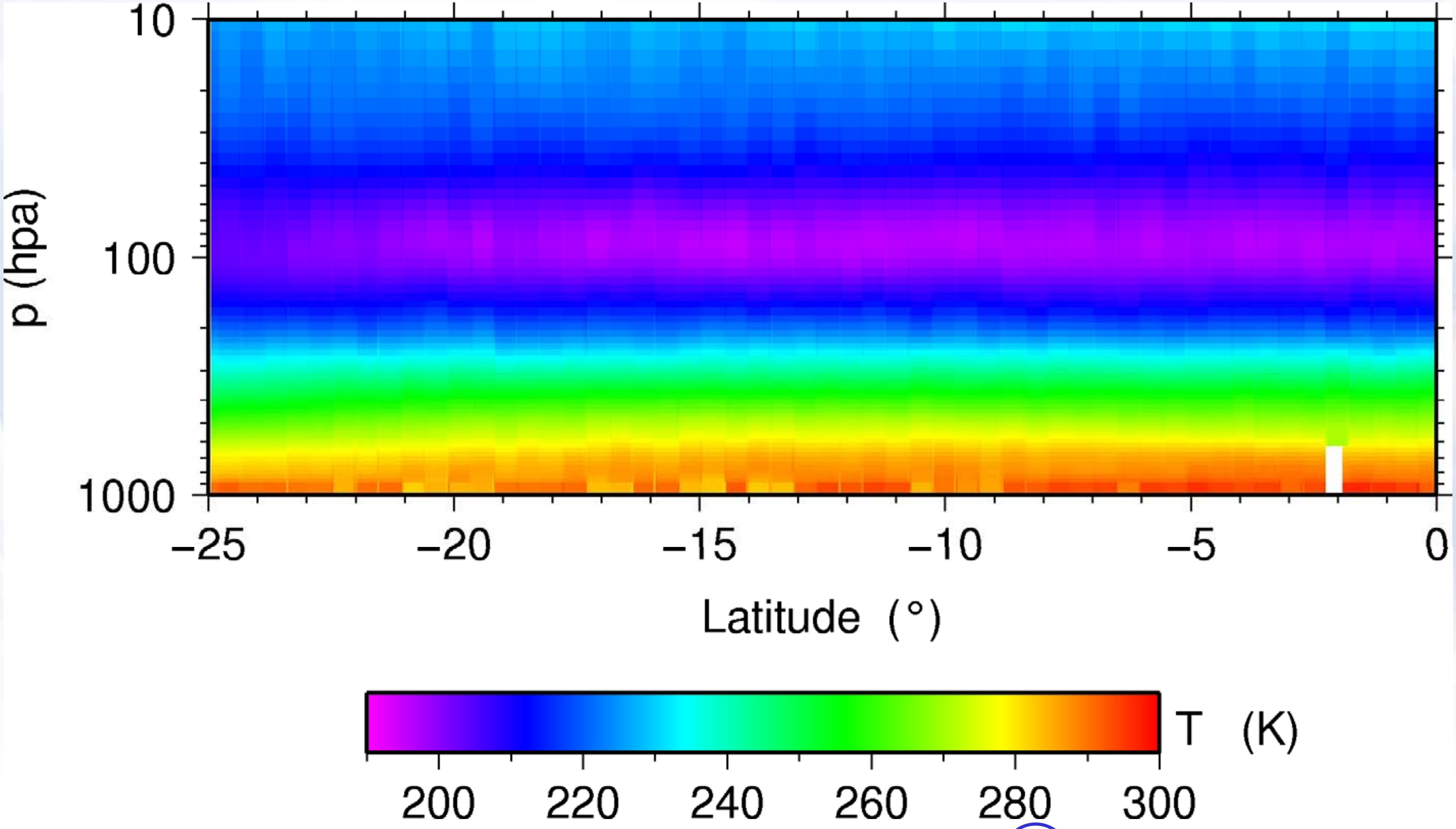




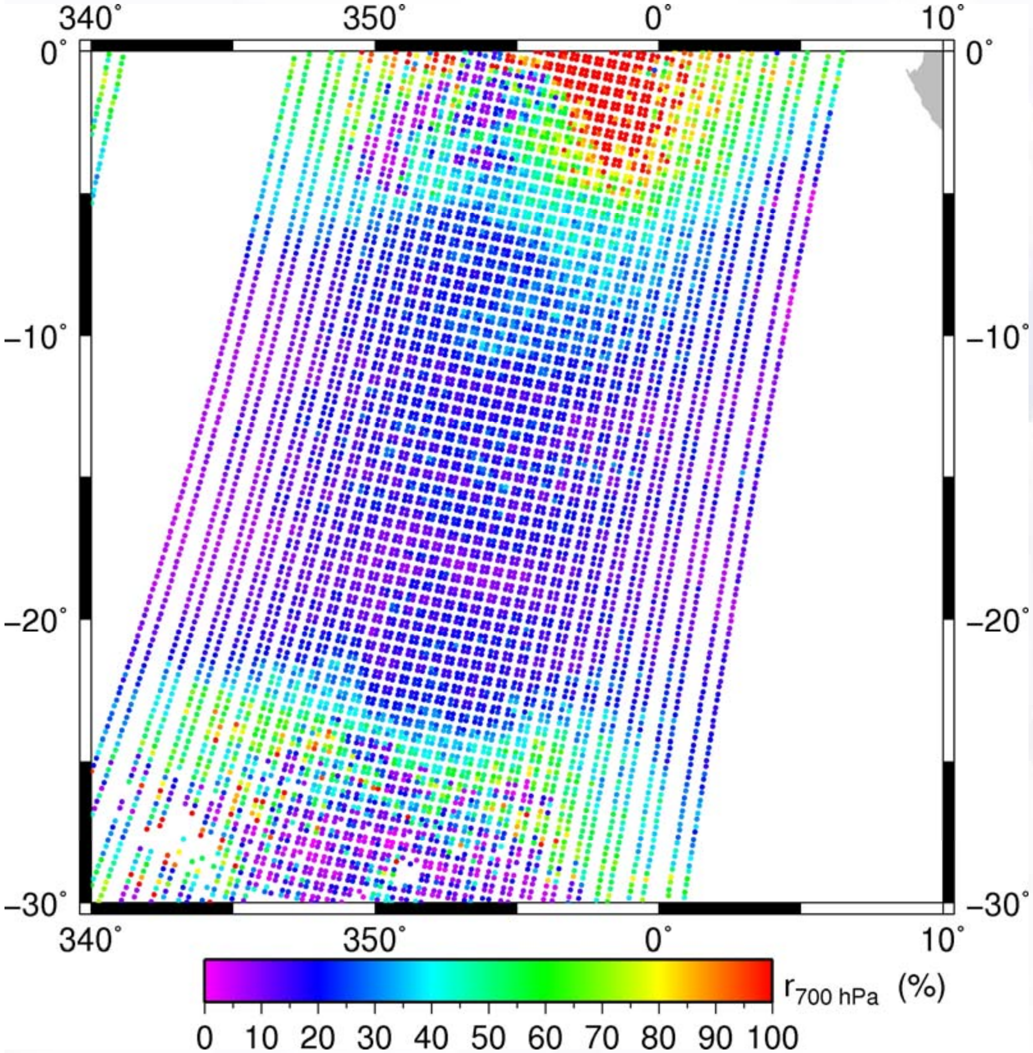
IASI: temperature retrievals on 10 June 2007 ~09:30 UTC

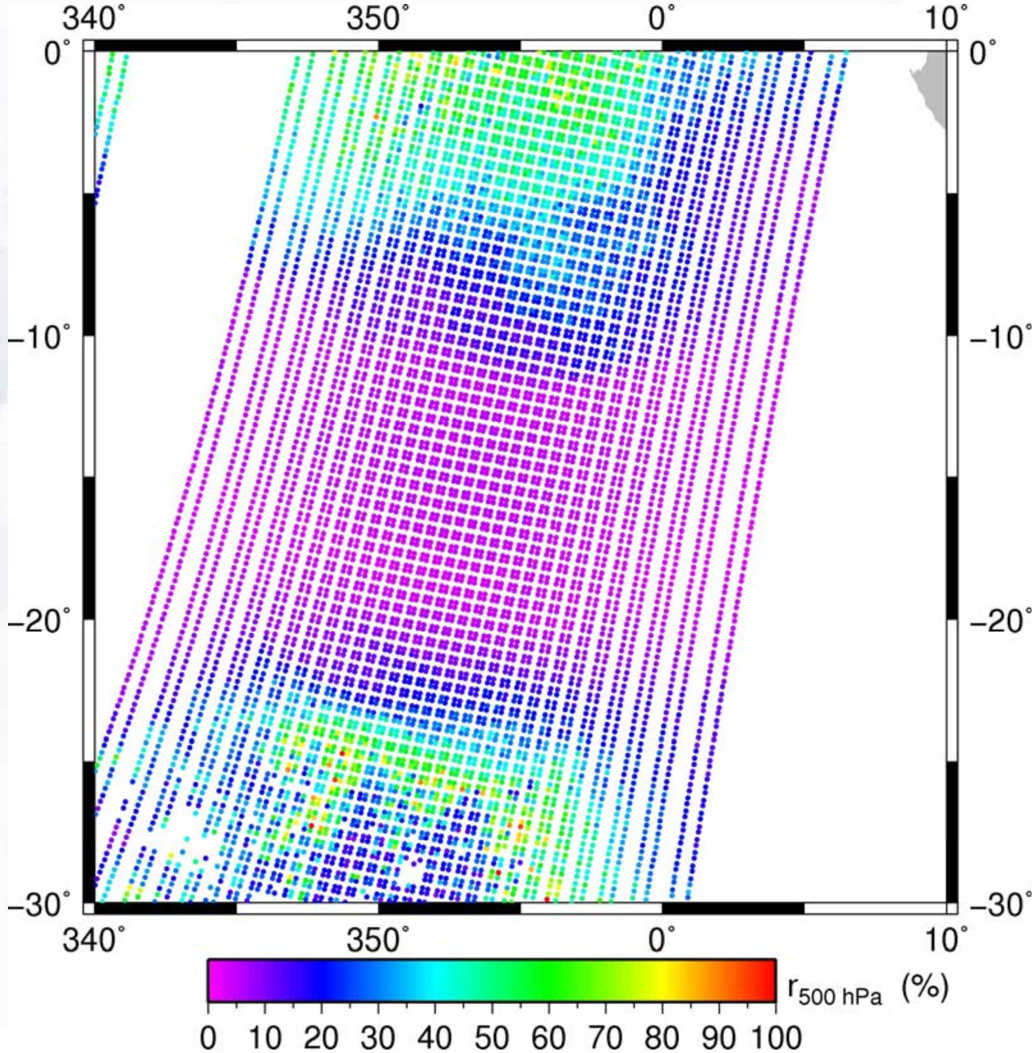


IASI: temperature retrievals on 10 June 2007 ~09:30 UTC cross section along ~7°W



IASI: humidity retrievals on 10 June 2007 ~09:30 UTC





IASI level 1 data format

- **Advantages of current data format**
  - User can use the IASI spectra like those from channel radiometers and extract useful parts
  - Interferometric characteristics are hidden from users, e.g. negative radiances

- **Disadvantages of current data format**
  - Large data volume: 2 Mbit/s
  - Quantisation in 16 bit words: slight degradation
  - Full usage of information hardly possible
  - Apodisation of spectra implies non-diagonal error covariances: complication in assimilation and retrieval

Possible future representation

- **Utilisation of empirical orthogonal functions**
  - Projection of IASI level 1A spectra (unapodised) on ~250 EOFs
  - Dissemination of EOF-scores

- **Advantage and new potential**
  - Data volume: 49 kbit/s
  - Re-constructed spectra are quasi noise-free
  - Direct assimilation of EOF scores instead of radiance spectra

Conclusion

- Metop-A has been launched and been operated successfully
- New instruments have been successfully commissioned
- Level 1 data are routinely disseminated to users
- Validation of the numerous products is ongoing

PCRTM: radiative transfer in EOF-space

- PCRTM calculates EOF-scores (*Y*) instead of spectral radiances (*R*)

$$\vec{Y} = U \times \vec{R}^{mono}$$

$$\frac{\partial Y_i}{\partial X} = \sum_{l=1}^{N_{mono}} a_l \frac{\partial R^{mono}(l)}{\partial X}$$

- Relationship between EOF scores and measured radiances:

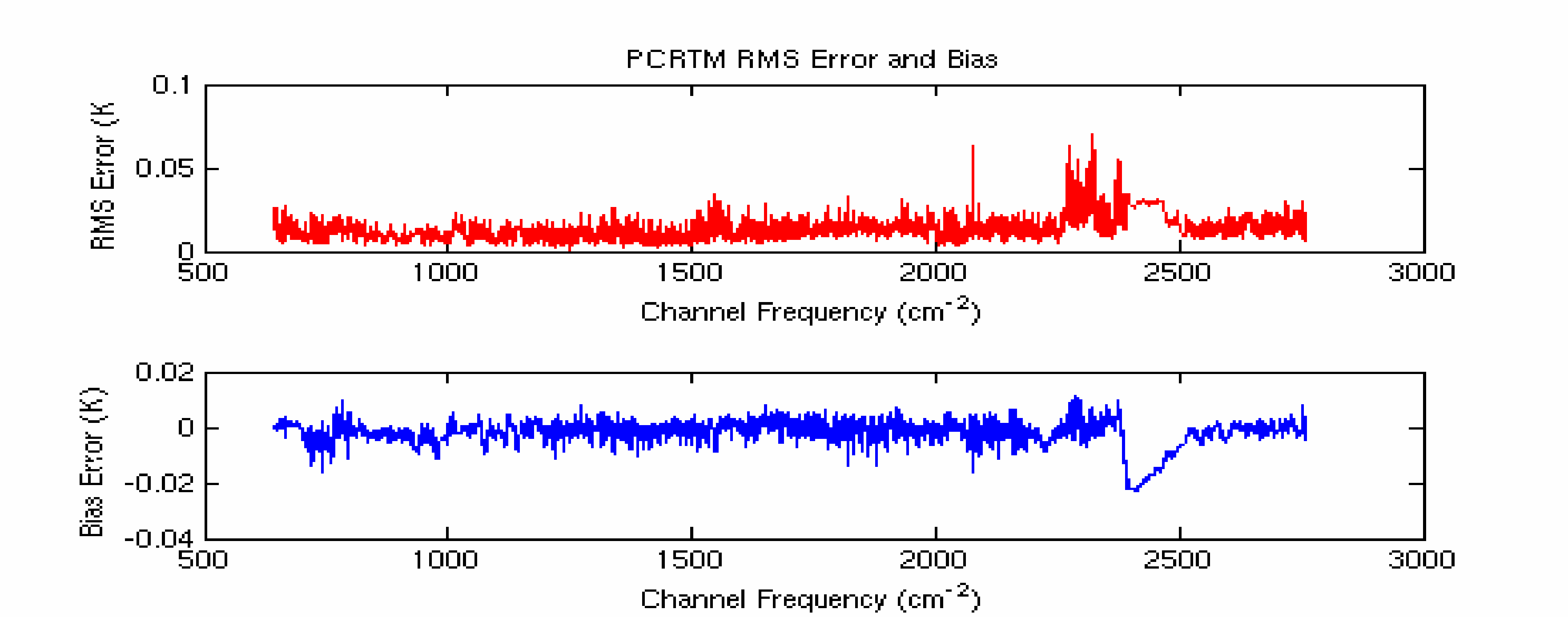
$$R_i^{chan} = \frac{\sum_{k=1}^{N} \phi_k R_k^{mono}}{\sum_{k=1}^{N} \phi_k}; \qquad \vec{Y} = U^T \times \vec{R}^{chan}$$

- Spectral radiances can be calculated from EOFs and corresponding scores:

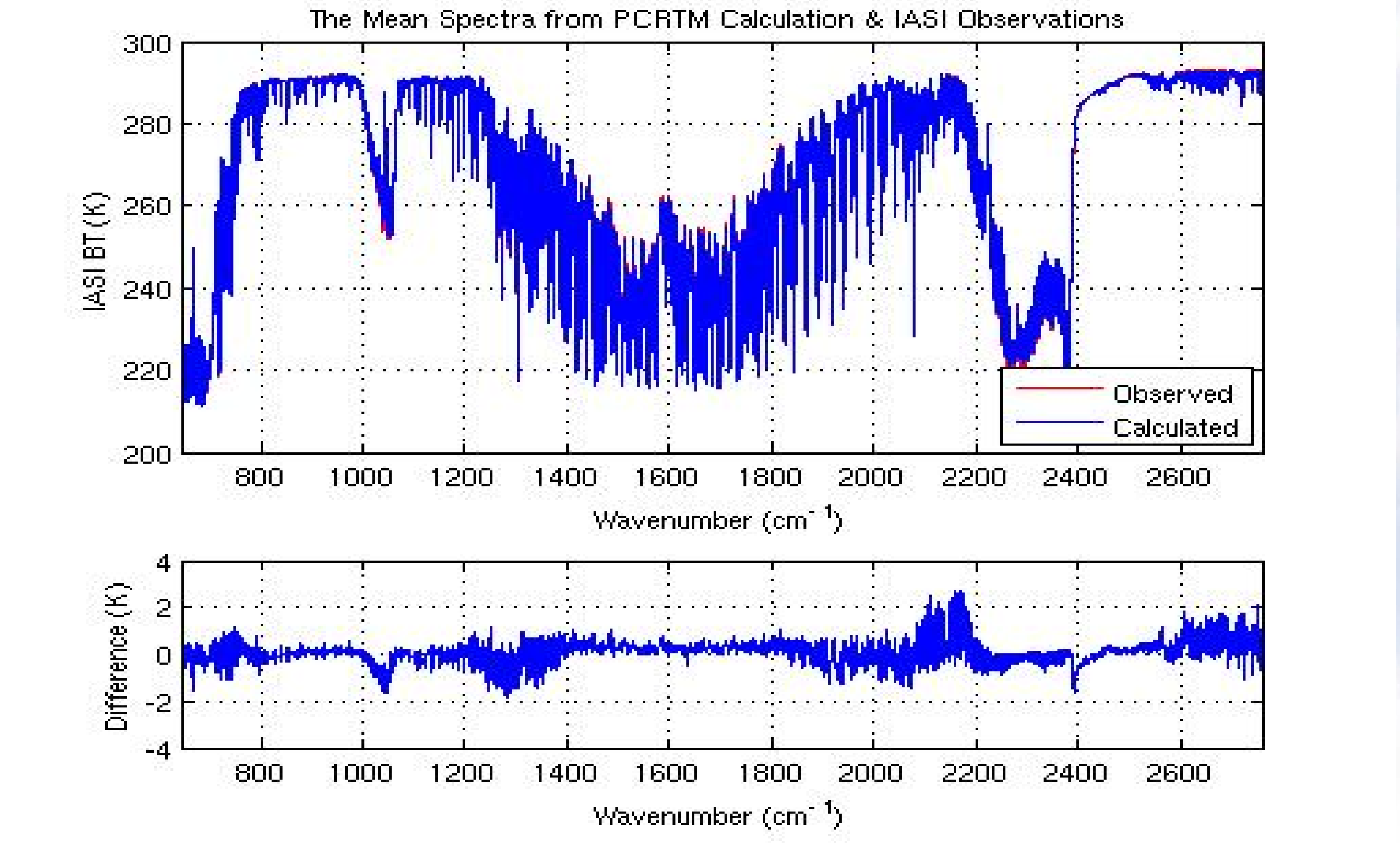
$$\vec{R}^{chan} = U \times \vec{Y} = \sum_{i=1}^{N_{EOF}} y_i \vec{U}_i + \vec{\varepsilon}$$

PCRTM: Training with LBL-model

- RMS error in brightness temperature: < 0.025 K
- Systematic errors in brightness temperature: (-0.0002 K, 0.0004 K)



PCRTM: validation with ECMWF and IASI data



PCRTM-retrieval: Levenberg-Marquardt-iteration

$$X_{n+1} - X_a = (K^T S_y^{-1} K + \lambda I + S_a^{-1})^{-1} K^T S_y^{-1} [(Y_n - Y_m) + K(X_n - X_a)]$$

50 retrieved EOF-Scores:

Surface temperature: 1
Temperature profile: 19
Humidity profile: 15
Ozone profile:10
Emissivity: 5

Variable	Radiance/state vector: dimensions	EOF-space: dimensions
Y	**8461**	**100**
X	**>100**	**50**
K	**> 8461x100**	**100x50**
S_y^{-1}	**8461x8461**	**100x100**
S_a	**> 100x100**	**50x50**
Calculation of *K* and *Y*	**~2 s**	**~0.1 s**

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