First lessons learnt from Metop

Peter Schlüssel

With thanks to Jörg Ackermann, Arlindo Arriaga, Thomas August, Hans Bonekamp, Xavier Calbet, Lars Fiedler, Tim Hultberg, Dieter Klaes, Xu Liu, François Montagner, Éamonn McKernan, Olusoji Oduleye, Bill Smith, Jon Taylor

EUMETSAT
Darmstadt, Germany

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

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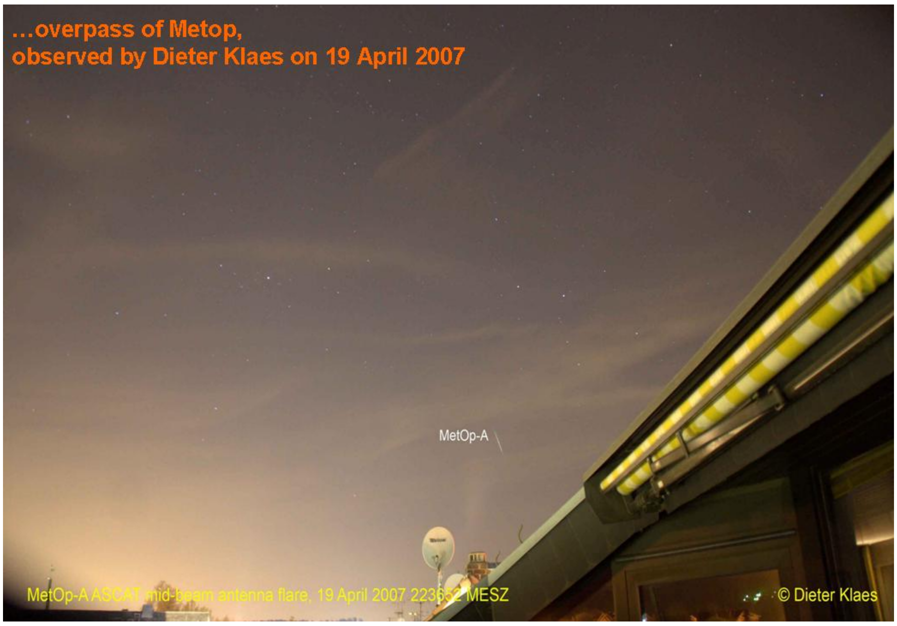
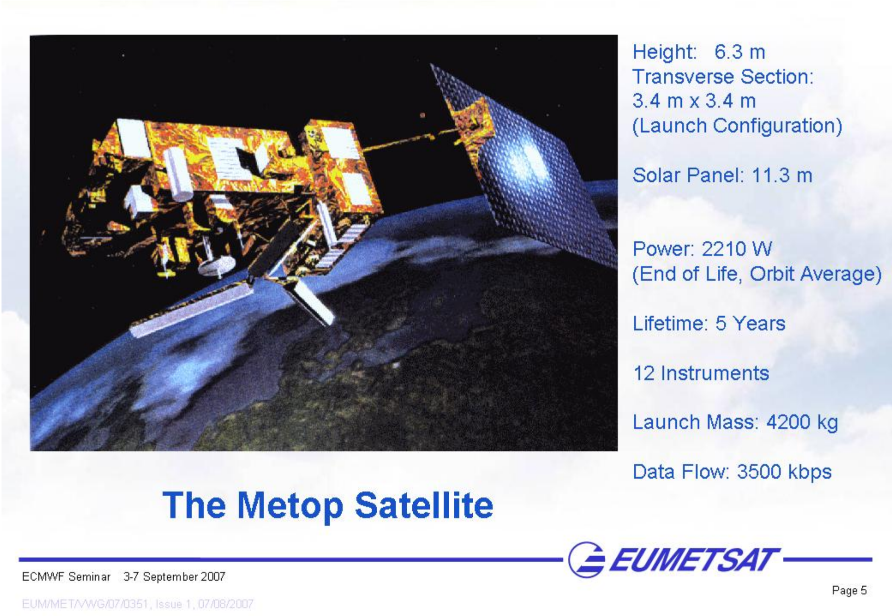
ECMWF Seminar 3-7 September 2007
EUM/MET/WG/07/0351, Issue 1, 07/08/2007
Page 2




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
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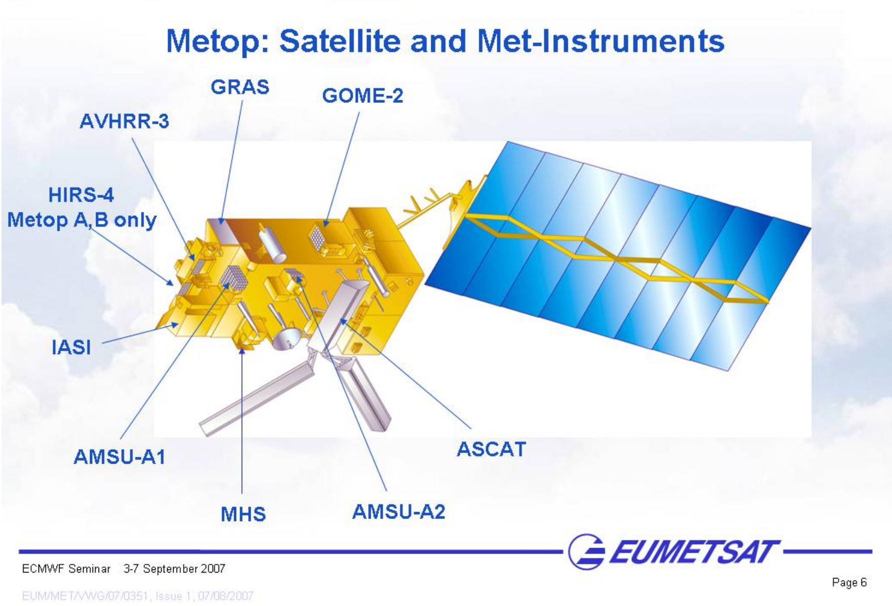
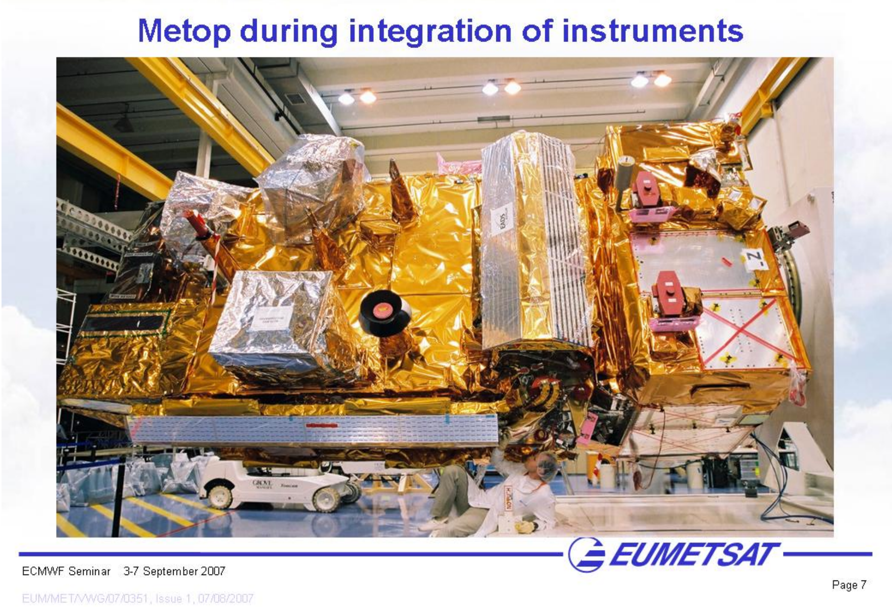
ECMWF Seminar 3-7 September 2007
EUM/MET/WG/07/0351, Issue 1, 07/08/2007
Page 5


Metop: Satellite and Met-Instruments
GRAS
GOME-2
AVHRR-3
HIRS-4
Metop A,B only
IASI
AMSU-A1
ASCAT
MHS
AMSU-A2
EUMETSAT
ECMWF Seminar 3-7 September 2007
EUM/MET/WG/07/0351, Issue 1, 07/08/2007
Page 6


Metop during integration of instruments
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ECMWF Seminar 3-7 September 2007
EUM/MET/WG/07/0351, Issue 1, 07/08/2007
Page 7

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

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ECMWF Seminar 3-7 September 2007

EUM/MET/VWG/07/0351, Issue 1, 07/08/2007

Page 8

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.

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ECMWF Seminar 3-7 September 2007

EUM/MET/VWG/07/0351, Issue 1, 07/08/2007

Page 9

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

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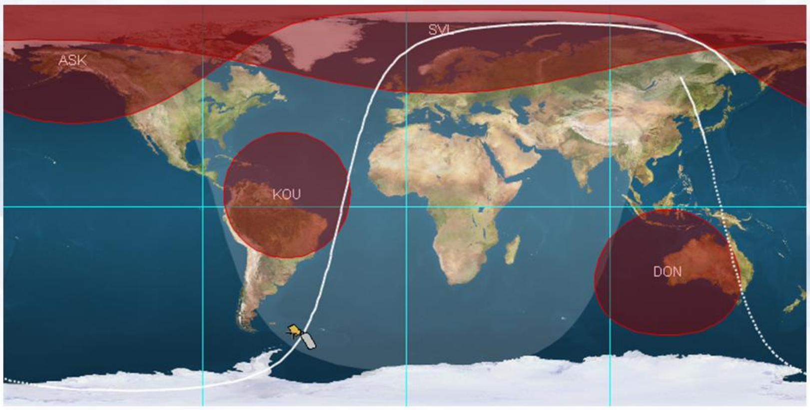
ECMWF Seminar 3-7 September 2007

EUM/MET/VWG/07/0351, Issue 1, 07/08/2007

Page 10

Metop-A control during SIOV



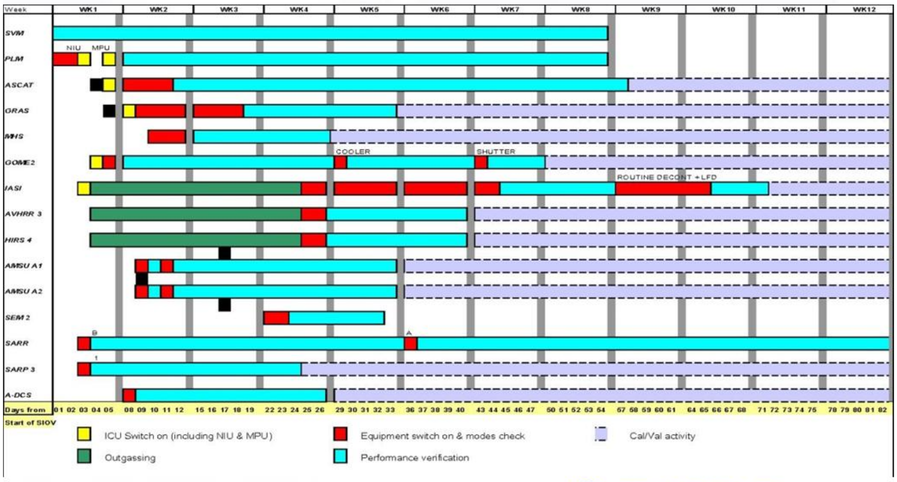
ECMWF Seminar 3-7 September 2007

EUM/MET/WG/07/0351, Issue 1, 07/08/2007

EUMETSAT

Page 11

Metop-A Satellite In-Orbit Verification



ECMWF Seminar 3-7 September 2007

EUM/MET/WG/07/0351, Issue 1, 07/08/2007

EUMETSAT

Page 12

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
  - .
  - .

ECMWF Seminar 3-7 September 2007

EUM/MET/WG/07/0351, Issue 1, 07/08/2007

EUMETSAT

Page 13

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

ECMWF Seminar 3-7 September 2007 Page 14
EUM/MET/WG/07/0351, Issue 1, 07/08/2007

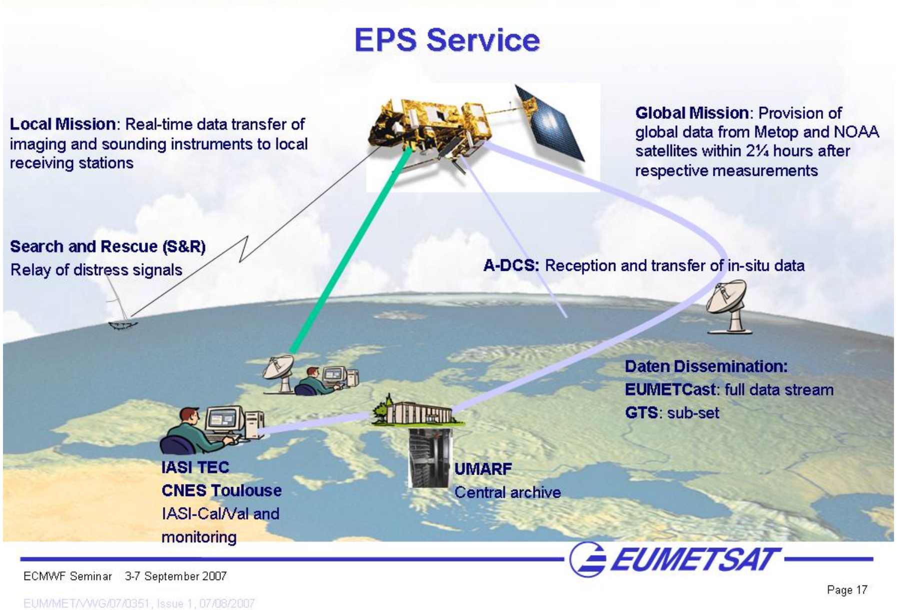
Partnership (2/2)

- 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

ECMWF Seminar 3-7 September 2007 Page 15
EUM/MET/WG/07/0351, Issue 1, 07/08/2007

Satellite Application Facilities (SAF)

ECMWF Seminar 3-7 September 2007 Page 16
EUM/MET/WG/07/0351, Issue 1, 07/08/2007



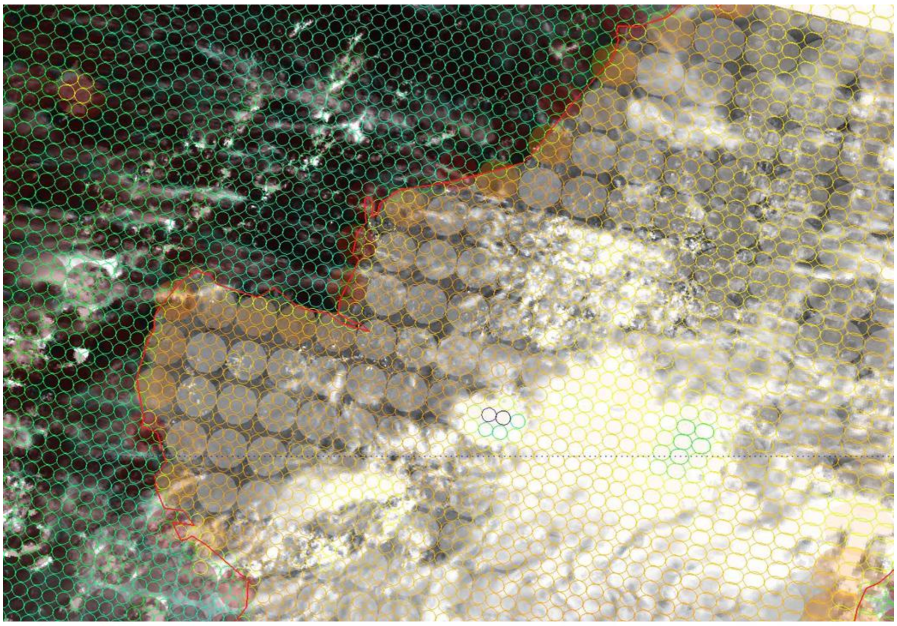
Data transfer and distribution

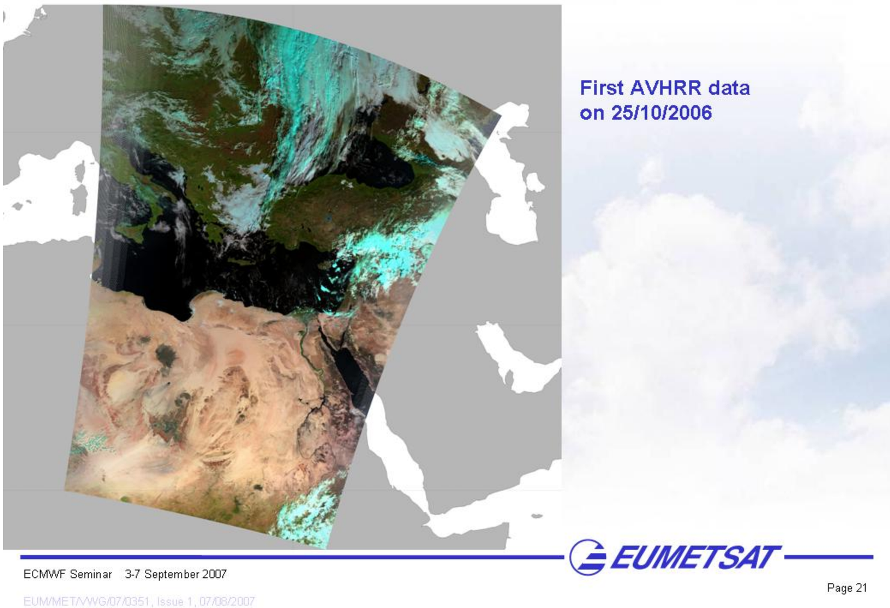
- From satellite to surface:
  - Data of one orbit is stored on board the satellite
  - Transfer to surface via X-band reception station on Svalbard after completion of each orbit
  - Transfer from Svalbard to Darmstadt via fibre link
  - Local users can directly read out the instrument data while the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

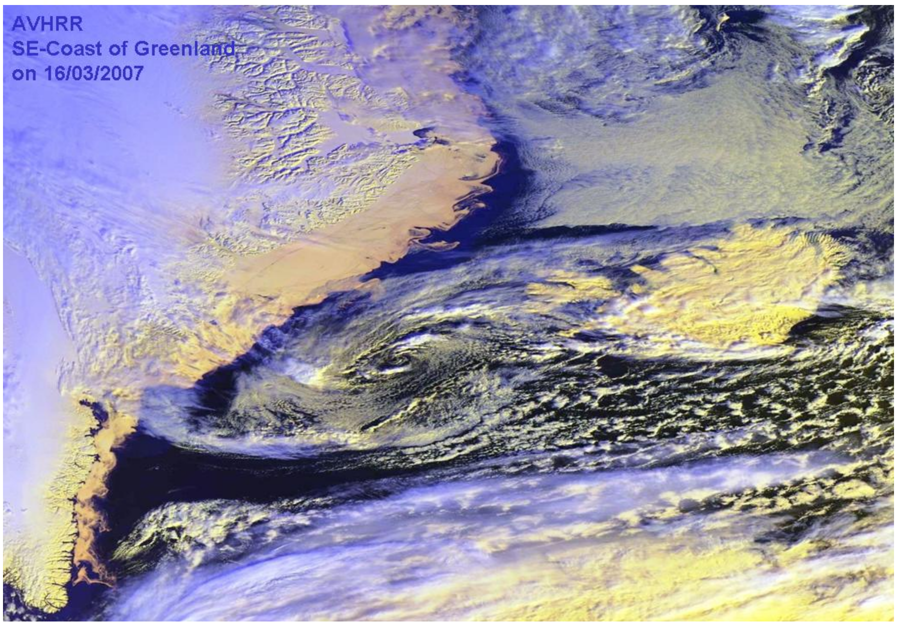
EUMETSAT

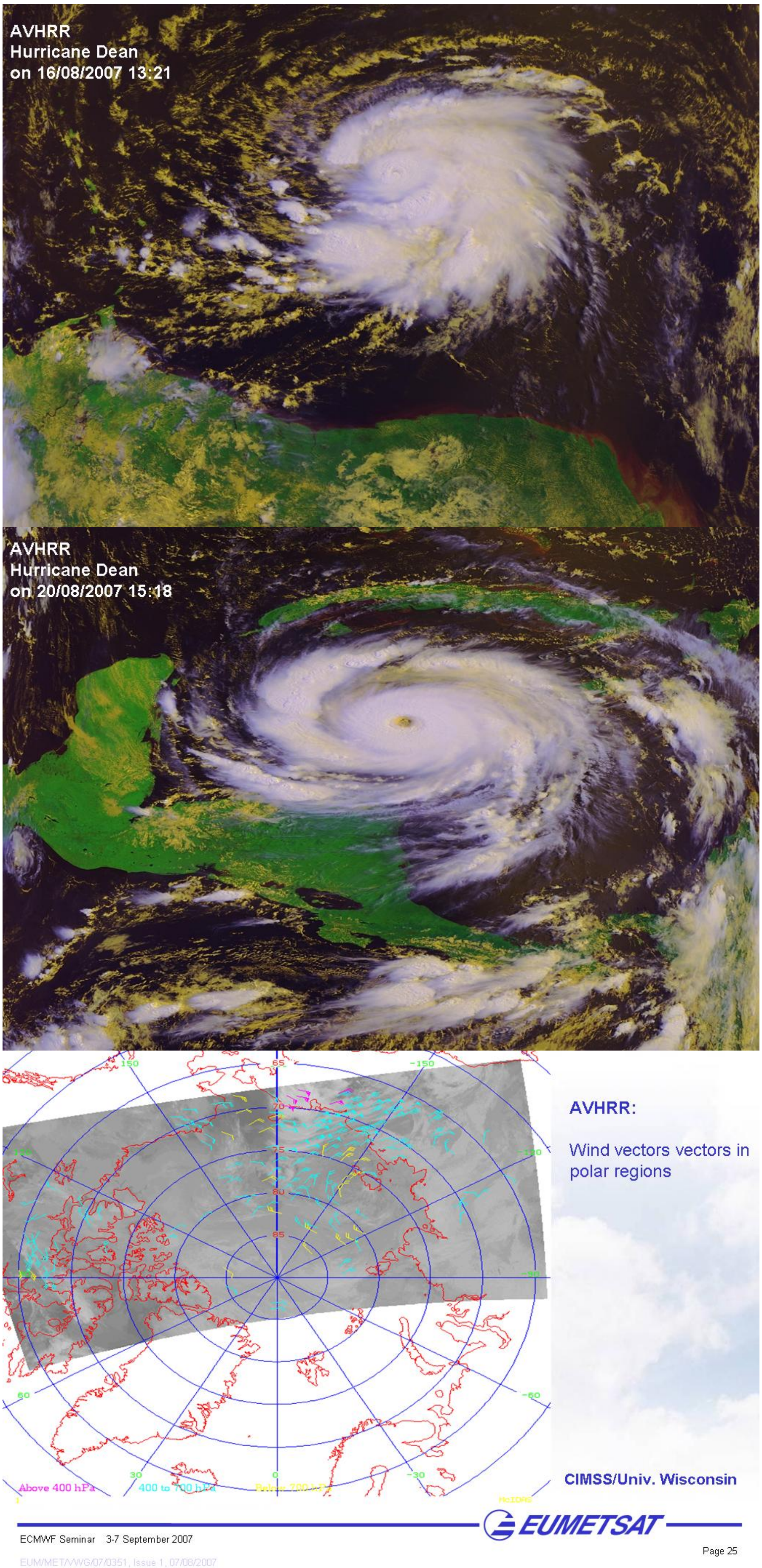
ECMWF Seminar 3-7 September 2007 — Page 18

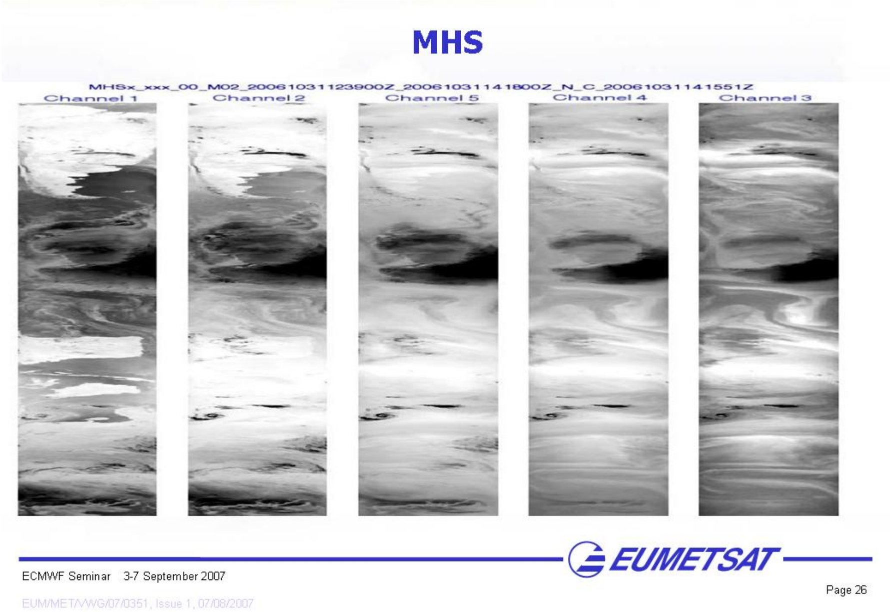
EUM/MET/WG/07/0351, Issue 1, 07/08/2007

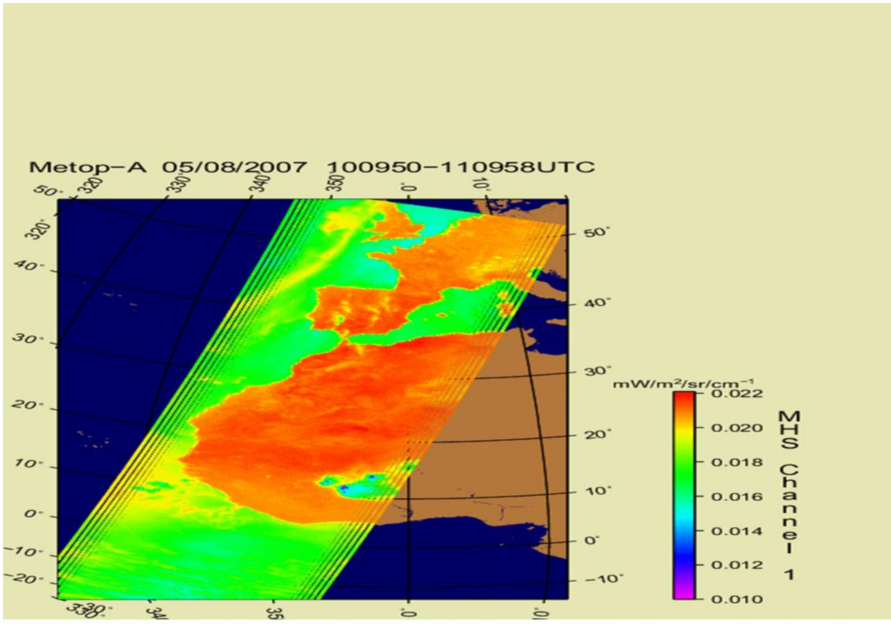


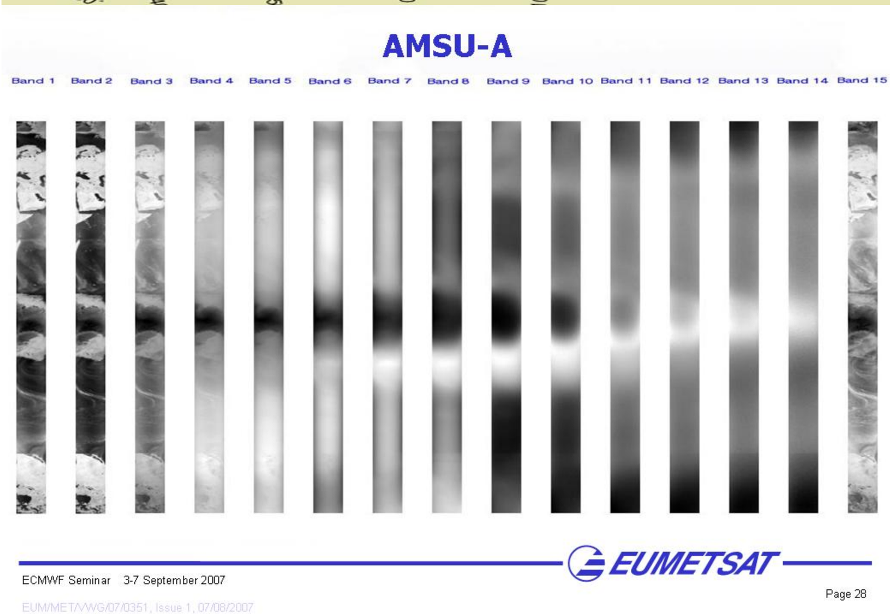

First AVHRR data
on 25/10/2006
EUMETSAT
ECMWF Seminar 3-7 September 2007
EUM/MET/VWG/07/0351, Issue 1, 07/08/2007
Page 21

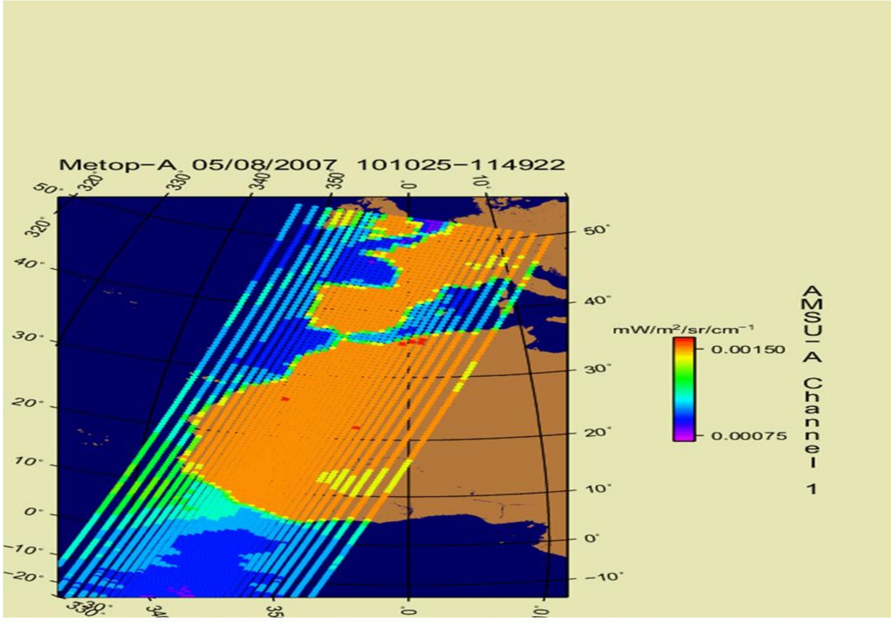

AVHRR
SE-Coast of Greenland
on 16/03/2007


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
EUMETSAT
ECMWF Seminar 3-7 September 2007
Page 25

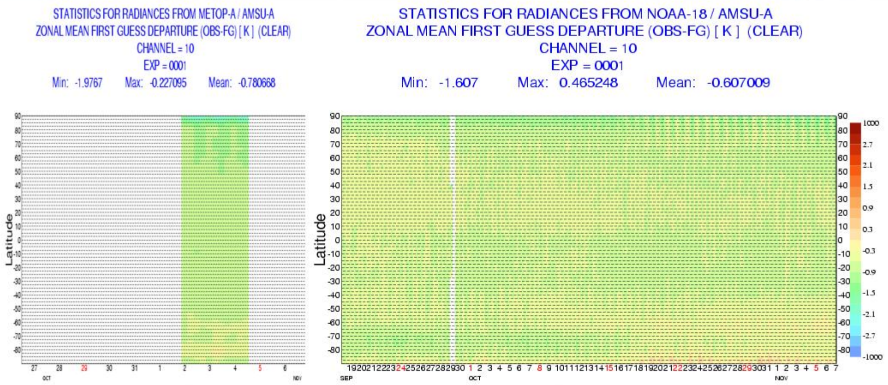

MHS
MHSx_xxx_00_M02_20061031123900Z_20061031141800Z_N_C_20061031141551Z
Channel 1
Channel 2
Channel 5
Channel 4
Channel 3
EUMETSAT
ECMWF Seminar 3-7 September 2007
Page 26


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


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
EUMETSAT
ECMWF Seminar 3-7 September 2007
Page 28



ECMWF monitoring the data from the beginning



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ECMWF Seminar 3-7 September 2007

EUM/MET/VWG/07/0351, Issue 1, 07/08/2007

Page 30

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				

EUMETSAT

ECMWF Seminar 3-7 September 2007

EUM/MET/VWG/07/0351, Issue 1, 07/08/2007

Page 31

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

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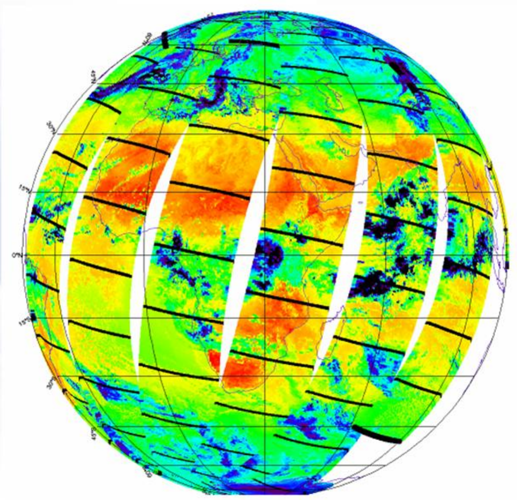
ECMWF Seminar 3-7 September 2007

EUM/MET/VWG/07/0351, Issue 1, 07/08/2007

Page 32



HIRS Channel 8

21 November 2006

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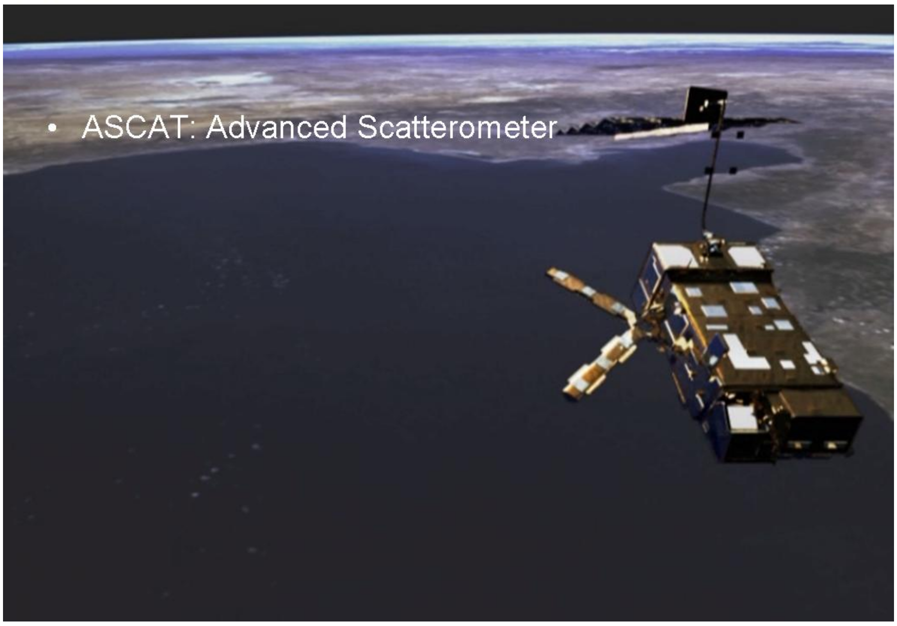
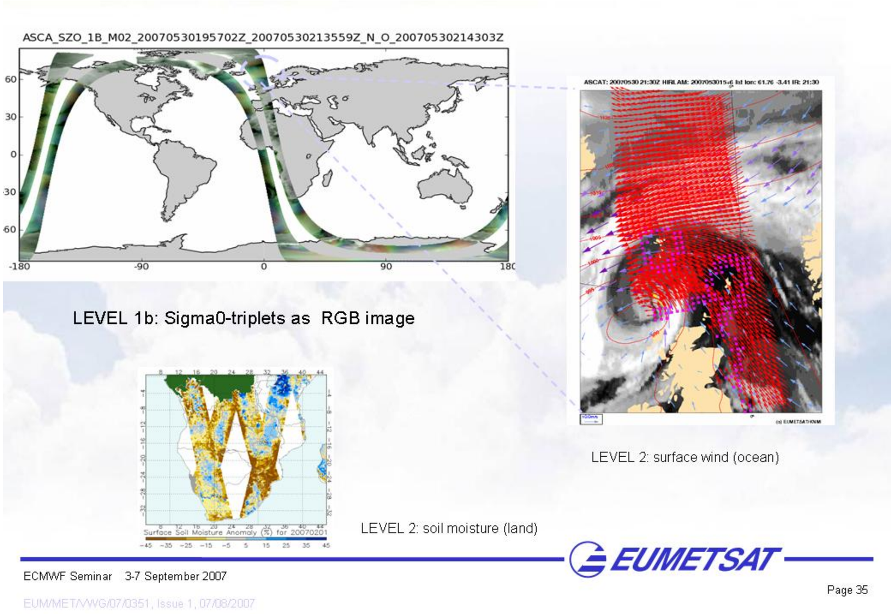
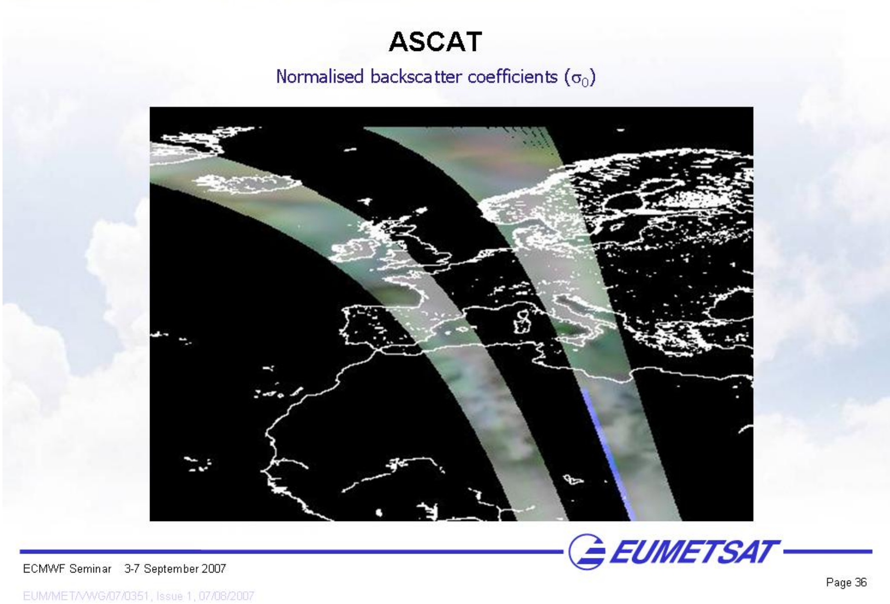
ECMWF Seminar 3-7 September 2007

EUM/MET/VWG/07/0351, Issue 1, 07/08/2007

Page 33




ASCA_SZO_1B_M02_20070530195702Z_20070530213559Z_N_O_20070530214303Z
LEVEL 1b: Sigma0-triplets as RGB image
LEVEL 2: surface wind (ocean)
LEVEL 2: soil moisture (land)
EUMETSAT
ECMWF Seminar 3-7 September 2007
EUM/MET/VWG/07/0351, Issue 1, 07/08/2007
Page 35


ASCAT
Normalised backscatter coefficients (σ0)
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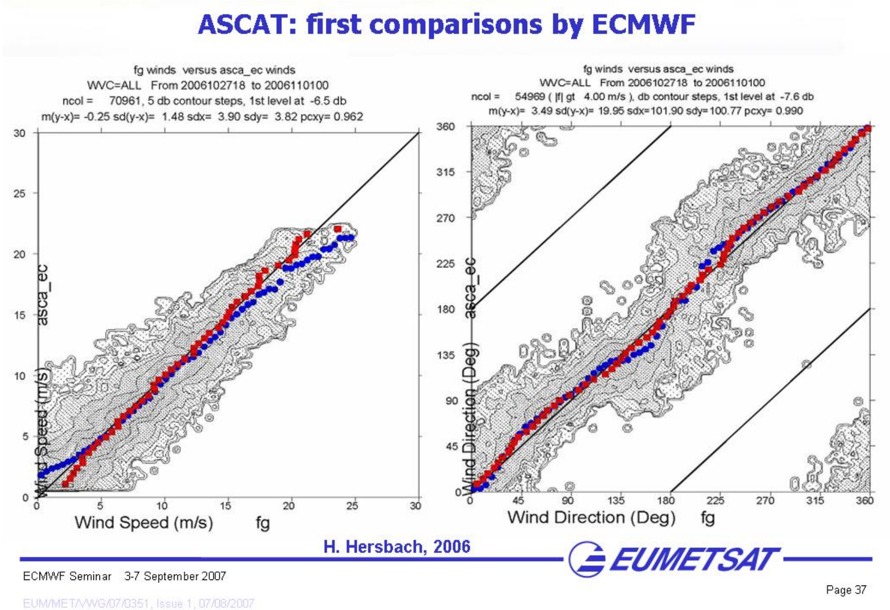
ECMWF Seminar 3-7 September 2007
EUM/MET/VWG/07/0351, Issue 1, 07/08/2007
Page 36


ASCAT: first comparisons by ECMWF
fg winds versus asca_ec winds
WVC=ALL From 2006102718 to 2006110100
ncol = 70961, 5 db contour steps, 1st level at -6.5 db
m(y-x)= -0.25 sd(y-x)= 1.48 sdx= 3.90 sdy= 3.82 pcxy= 0.962
Wind Speed (m/s) asca_ec
Wind Speed (m/s) fg
fg winds versus asca_ec winds
WVC=ALL From 2006102718 to 2006110100
ncol = 54969 (|f| gt 4.00 m/s), db contour steps, 1st level at -7.6 db
m(y-x)= 3.49 sd(y-x)= 19.95 sdx=101.90 sdy=100.77 pcxy= 0.990
Wind Direction (Deg) asca_ec
Wind Direction (Deg) fg
H. Hersbach, 2006
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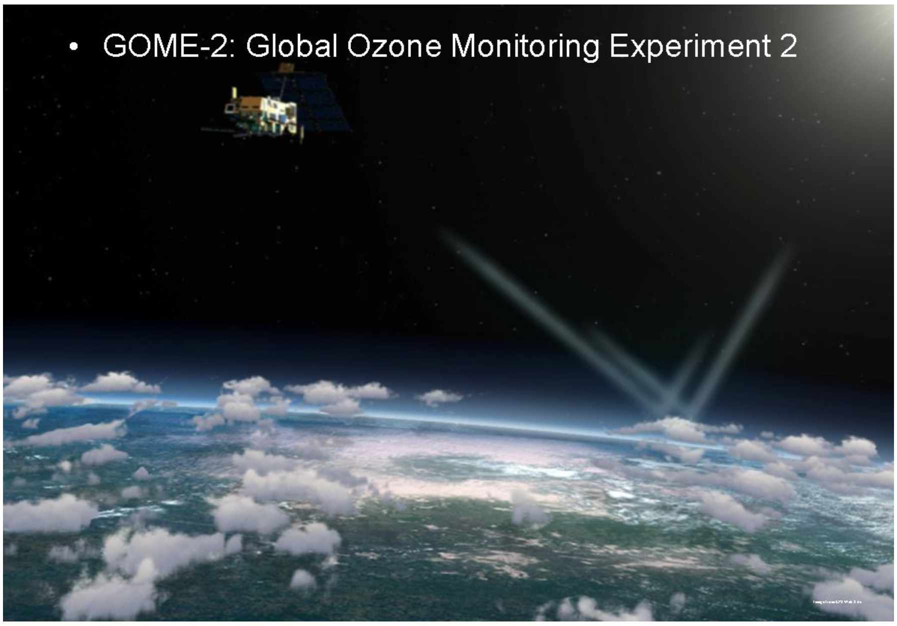
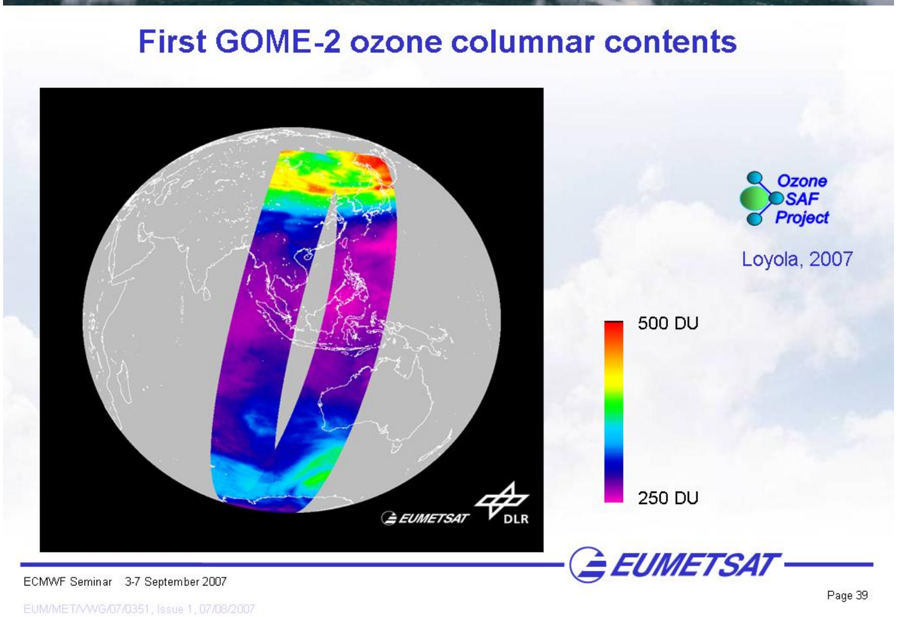
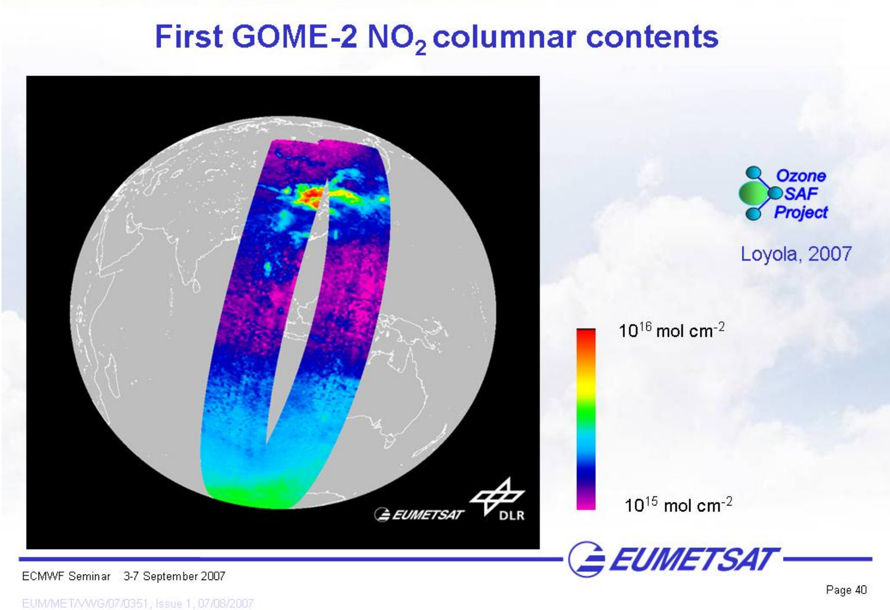
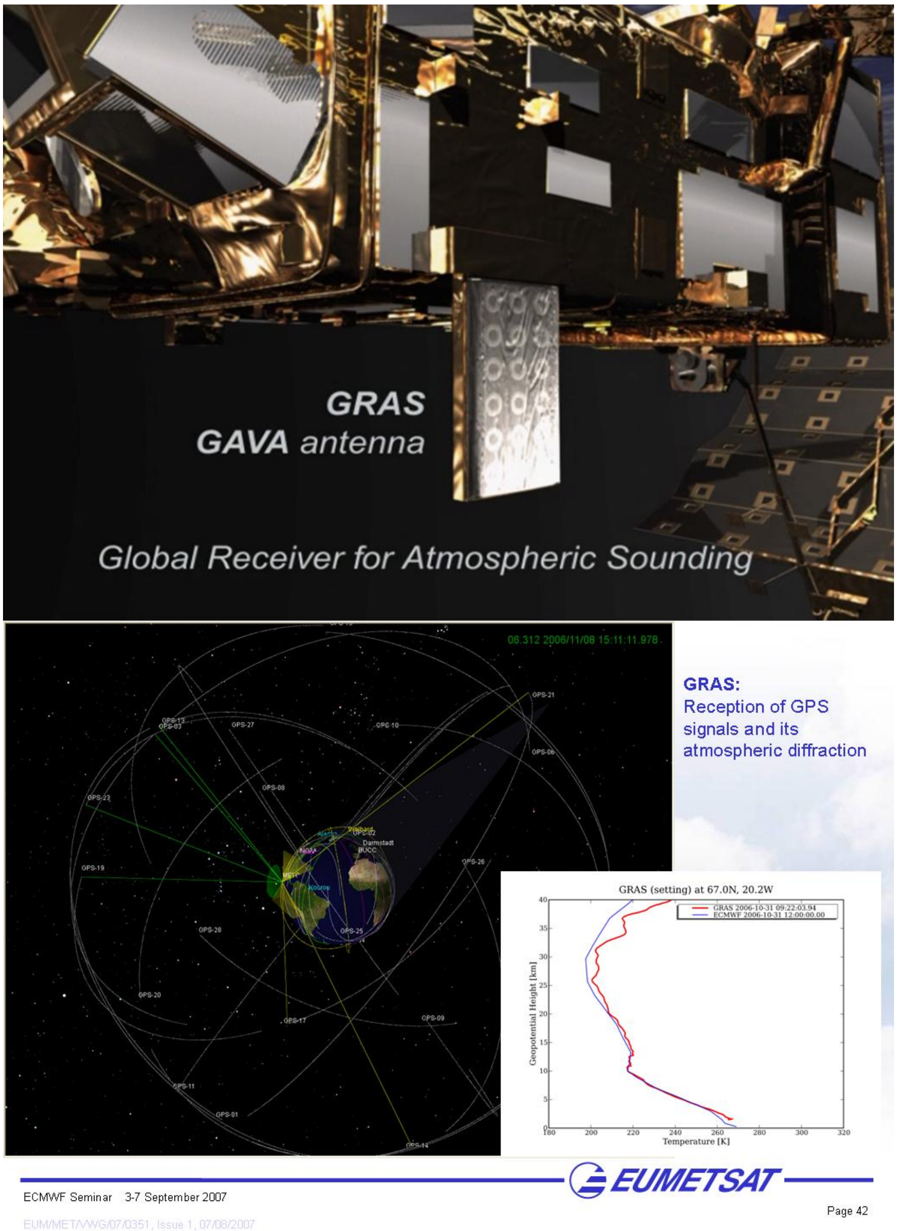
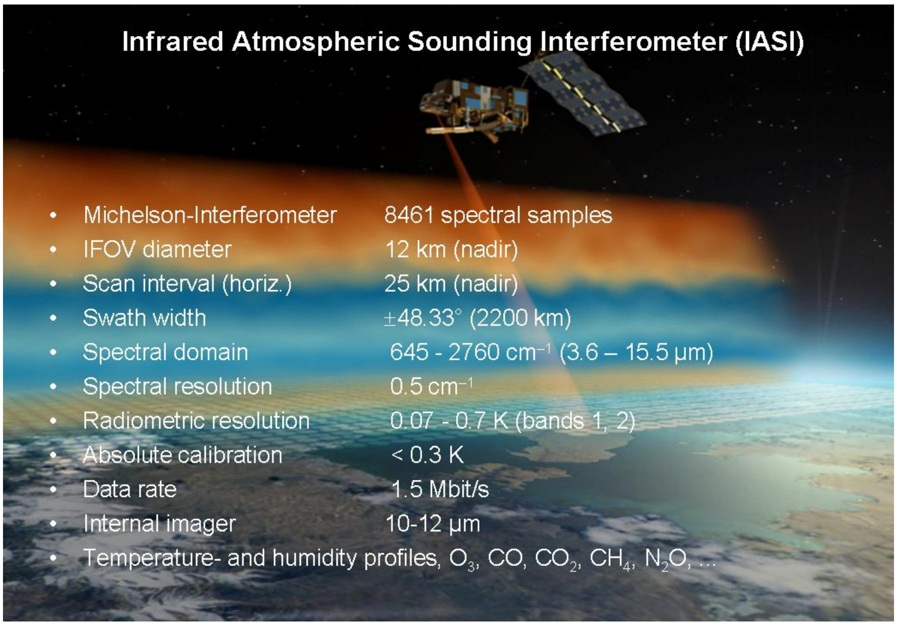
ECMWF Seminar 3-7 September 2007
EUM/MET/VWG/07/0351, Issue 1, 07/08/2007
Page 37

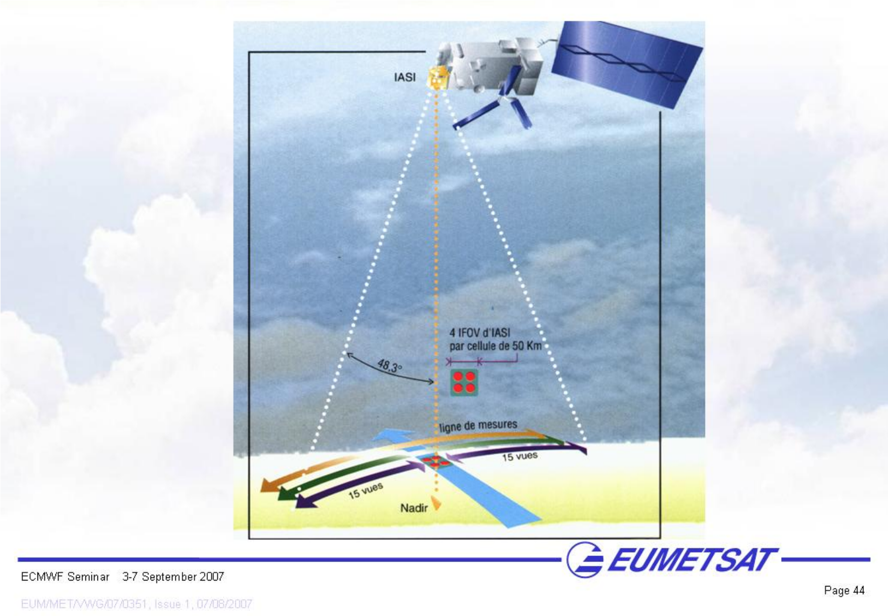

• GOME-2: Global Ozone Monitoring Experiment 2


First GOME-2 ozone columnar contents
Ozone SAF Project
Loyola, 2007
500 DU
250 DU
EUMETSAT
DLR
EUMETSAT
ECMWF Seminar 3-7 September 2007
EUM/MET/VWG/07/0351, Issue 1, 07/08/2007
Page 39


First GOME-2 NO_2 columnar contents
Ozone SAF Project
Loyola, 2007
10^{16} mol cm^{-2}
10^{15} mol cm^{-2}
EUMETSAT
DLR
EUMETSAT
ECMWF Seminar 3-7 September 2007
EUM/MET/VWG/07/0351, Issue 1, 07/08/2007
Page 40


GRAS
GAVA antenna
Global Receiver for Atmospheric Sounding
GRAS:
Reception of GPS signals and its atmospheric diffraction
GRAS (setting) at 67.0N, 20.2W
Geopotential Height [km]
Temperature [K]
ECMWF Seminar 3-7 September 2007
EUMETSAT
Page 42


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
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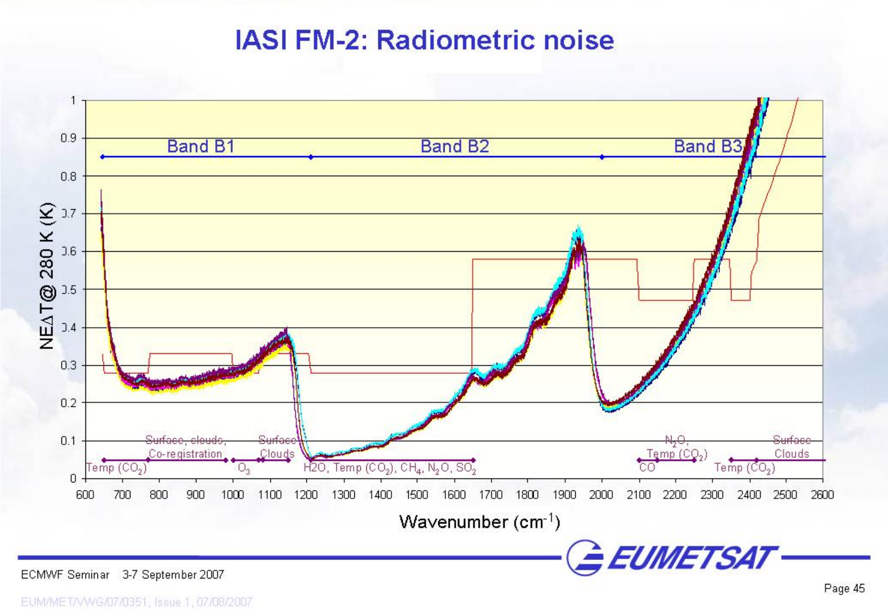
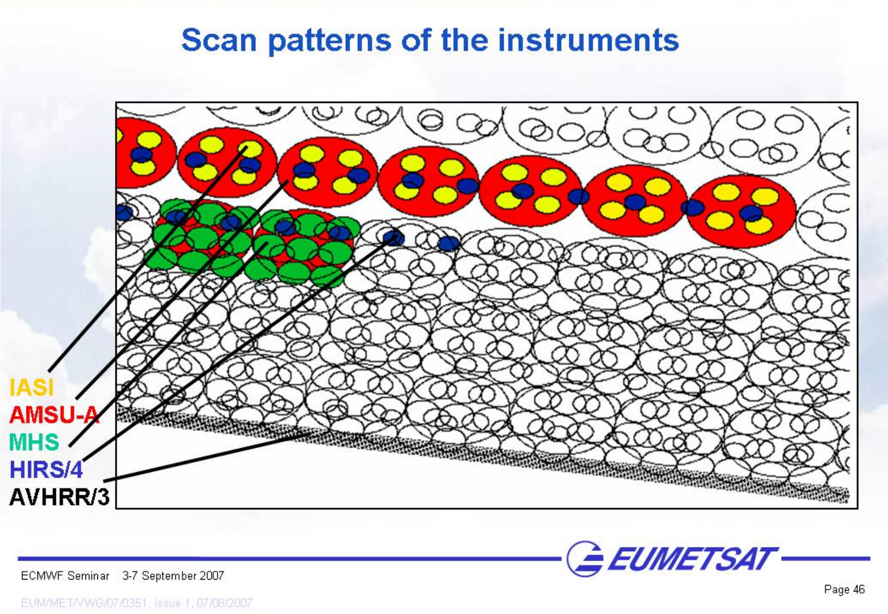
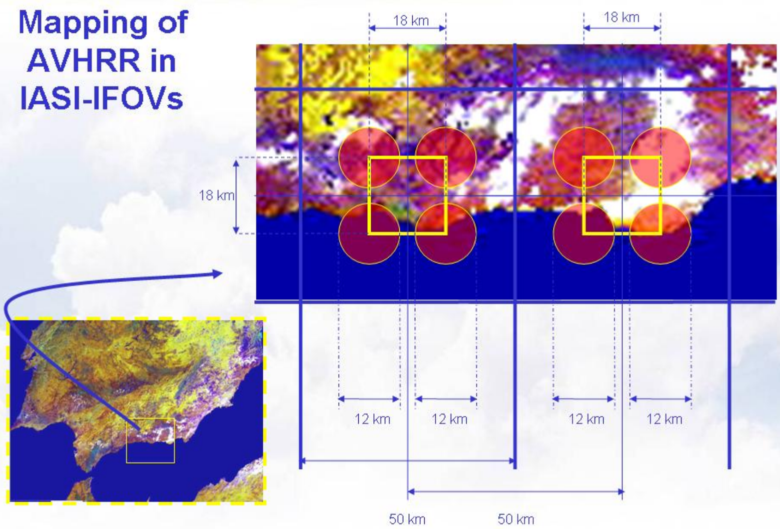
ECMWF Seminar 3-7 September 2007
Page 44
EUM/MET/VWG/07/0351, Issue 1, 07/08/2007


IASI FM-2: Radiometric noise
Band B1
Band B2
Band B3
NEΔT@ 280 K (K)
Wavenumber (cm-1)
Surface, clouds, Co-registration
Surface Clouds
Temp (CO2)
O3
H2O, Temp (CO2), CH4, N2O, SO2
N2O, Temp (CO2)
CO
Temp (CO2)
Surface Clouds
EUMETSAT
ECMWF Seminar 3-7 September 2007
Page 45
EUM/MET/VWG/07/0351, Issue 1, 07/08/2007


Scan patterns of the instruments
IASI
AMSU-A
MHS
HIRS/4
AVHRR/3
EUMETSAT
ECMWF Seminar 3-7 September 2007
Page 46
EUM/MET/VWG/07/0351, Issue 1, 07/08/2007



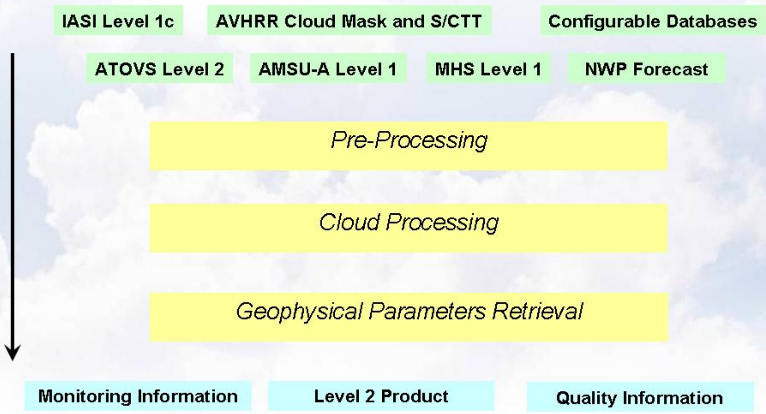
EUMETSAT

ECMWF Seminar 3-7 September 2007

Page 47

EUM/MET/VWG/07/0351, Issue 1, 07/08/2007

IASI Level 2 product generation



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ECMWF Seminar 3-7 September 2007

Page 48

EUM/MET/VWG/07/0351, Issue 1, 07/08/2007

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

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ECMWF Seminar 3-7 September 2007

Page 49

EUM/MET/VWG/07/0351, Issue 1, 07/08/2007

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

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ECMWF Seminar 3-7 September 2007

EUM/MET/VWG/07/0351, Issue 1, 07/08/2007

Page 50

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

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ECMWF Seminar 3-7 September 2007

EUM/MET/VWG/07/0351, Issue 1, 07/08/2007

Page 51

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

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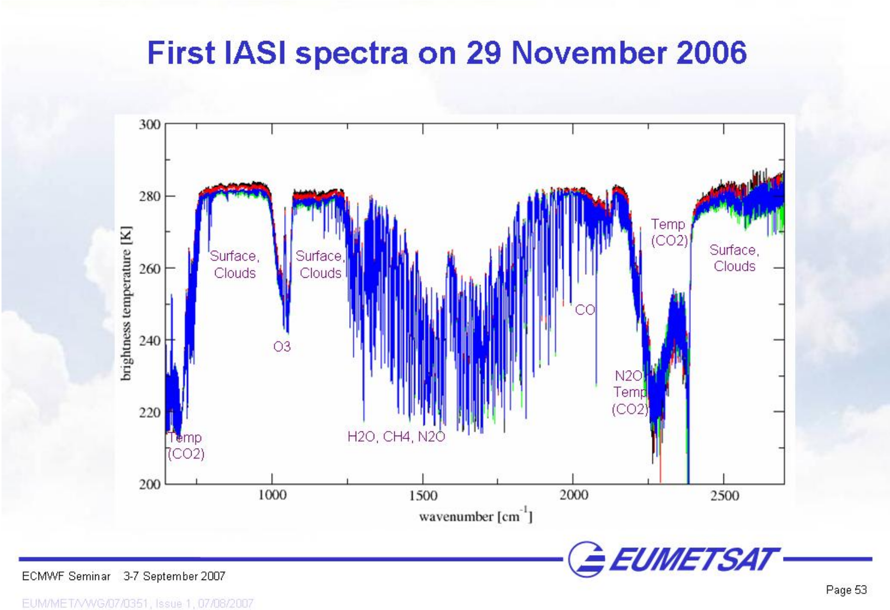
ECMWF Seminar 3-7 September 2007

EUM/MET/VWG/07/0351, Issue 1, 07/08/2007

Page 52


First IASI spectra on 29 November 2006
brightness temperature [K]
wavenumber [cm^{-1}]
Surface, Clouds
Surface, Clouds
O3
Temp (CO2)
H2O, CH4, N2O
CO
N2O Temp (CO2)
Temp (CO2)
Surface, Clouds
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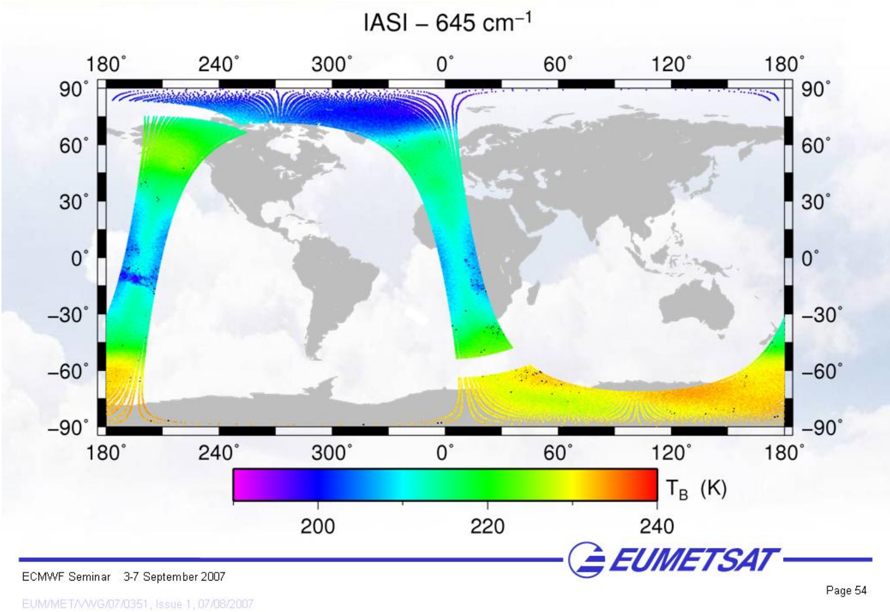
Page 53


IASI – 645 cm^{-1}
T_B (K)
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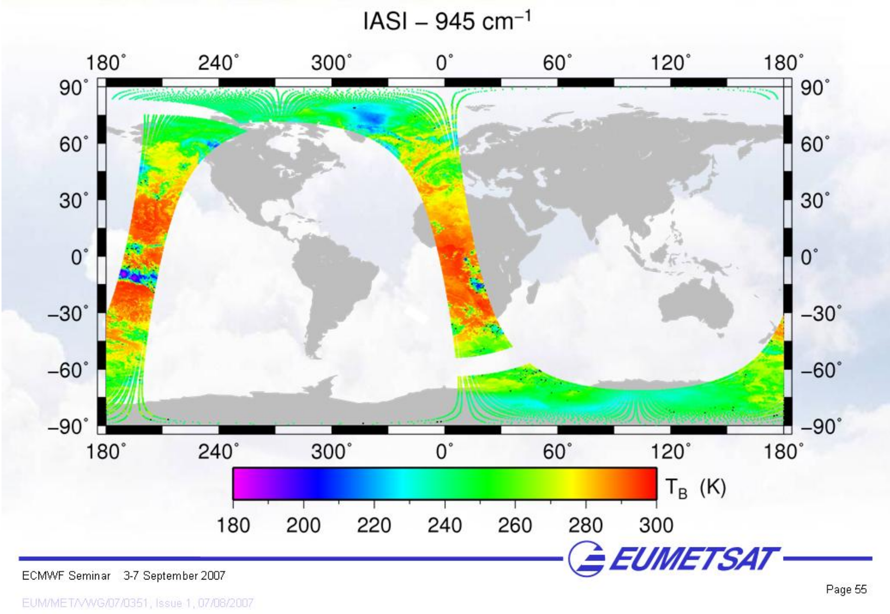
Page 54


IASI – 945 cm^{-1}
T_B (K)
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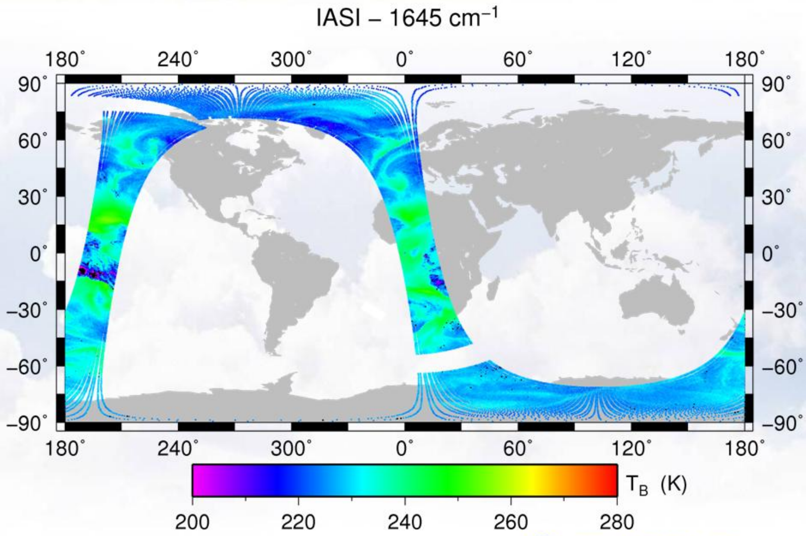
ECMWF Seminar 3-7 September 2007
Page 55



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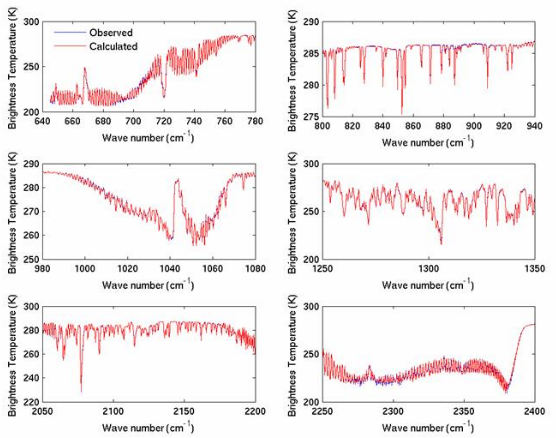
ECMWF Seminar 3-7 September 2007

EUM/MET/VWG/07/0351, Issue 1, 07/08/2007

Page 56

Comparisons of simulated and measured spectra



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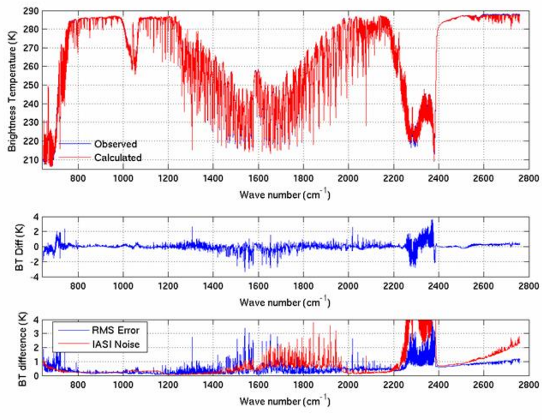
EUM/MET/VWG/07/0351, Issue 1, 07/08/2007

Page 57

Comparisons of simulated and measured spectra



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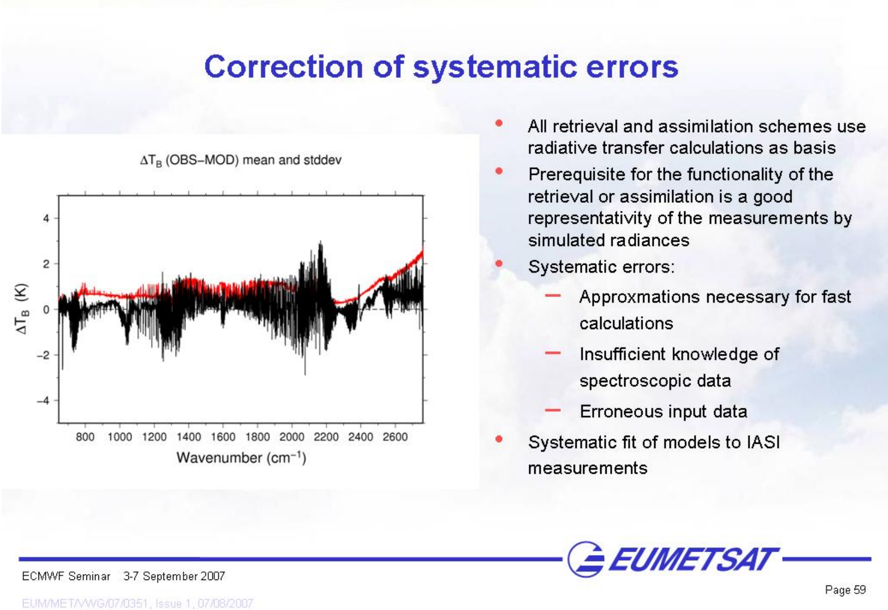
ECMWF Seminar 3-7 September 2007

EUM/MET/VWG/07/0351, Issue 1, 07/08/2007

Page 58


Correction of systematic errors
ΔT_B (OBS−MOD) mean and stddev
ΔT_B (K)
Wavenumber (cm⁻¹)
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
EUMETSAT
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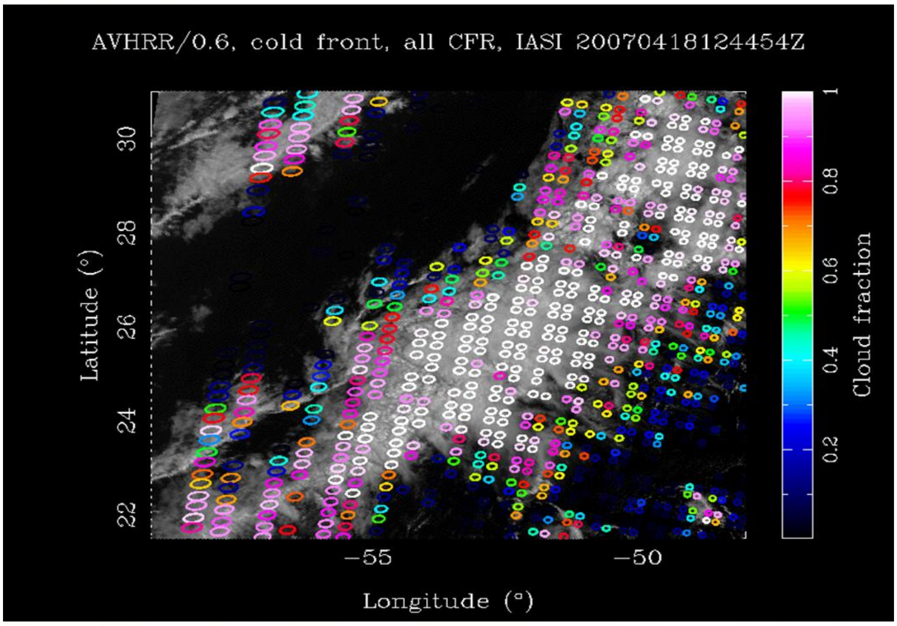
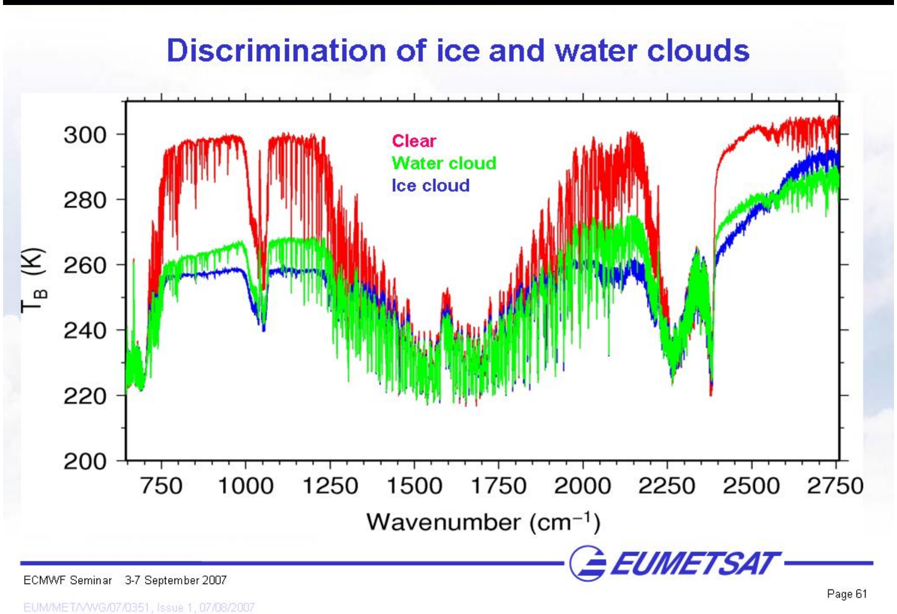
Page 59
EUM/MET/VWG/07/0351, Issue 1, 07/08/2007


AVHRR/0.6, cold front, all CFR, IASI 20070418124454Z
Latitude (°)
Longitude (°)
Cloud fraction


Discrimination of ice and water clouds
Clear
Water cloud
Ice cloud
T_B (K)
Wavenumber (cm⁻¹)
EUMETSAT
ECMWF Seminar 3-7 September 2007
Page 61
EUM/MET/VWG/07/0351, Issue 1, 07/08/2007

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

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EUM/MET/VWG/07/0351, Issue 1, 07/08/2007

Page 62

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

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EUM/MET/VWG/07/0351, Issue 1, 07/08/2007

Page 63

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)

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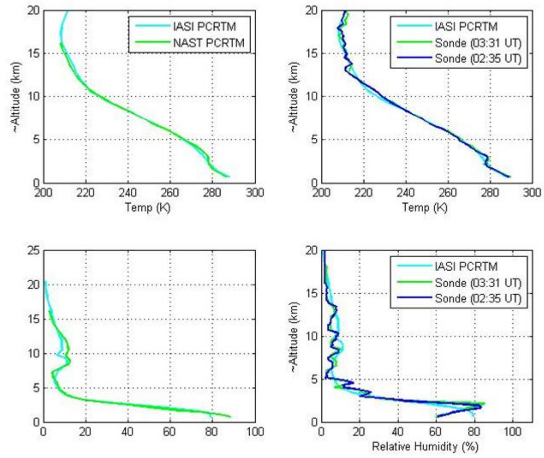
EUM/MET/VWG/07/0351, Issue 1, 07/08/2007

Page 64

Comparison: IASI / NAST-I / radiosonde



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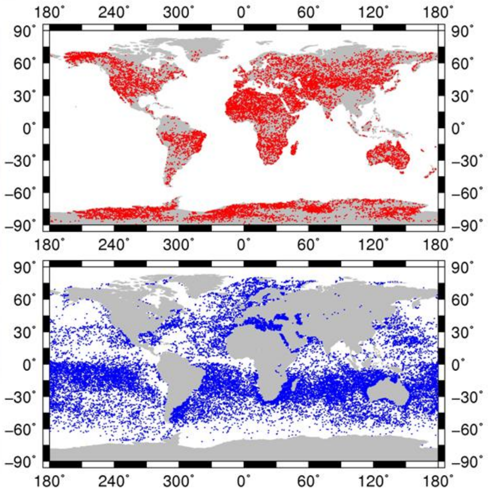
EUM/MET/VWG/07/0351, Issue 1, 07/08/2007

Page 65



Comparison: ECMWF / IASI

Clear situations
May – June 2007

Land: 1330 match-ups

Ocean: 21810 match-ups

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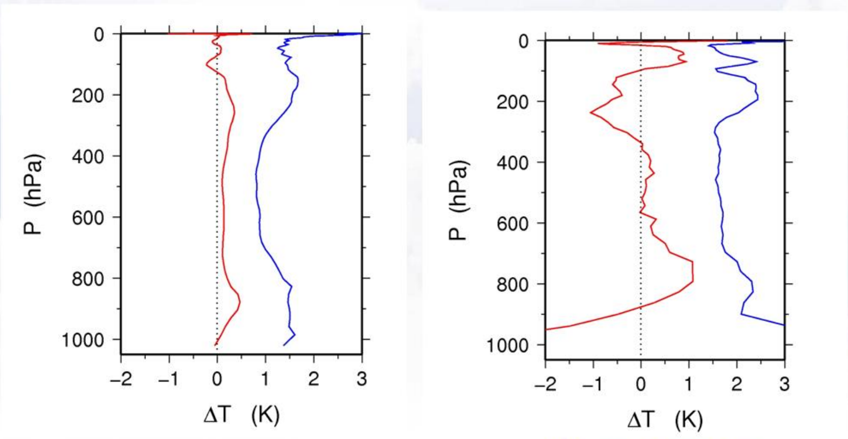
Page 66

Comparison: ECMWF – IASI L2



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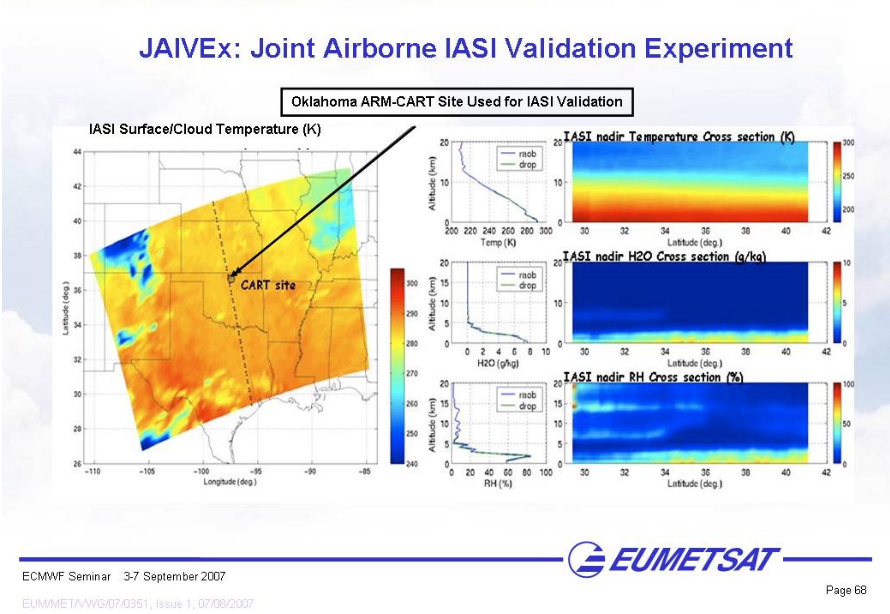
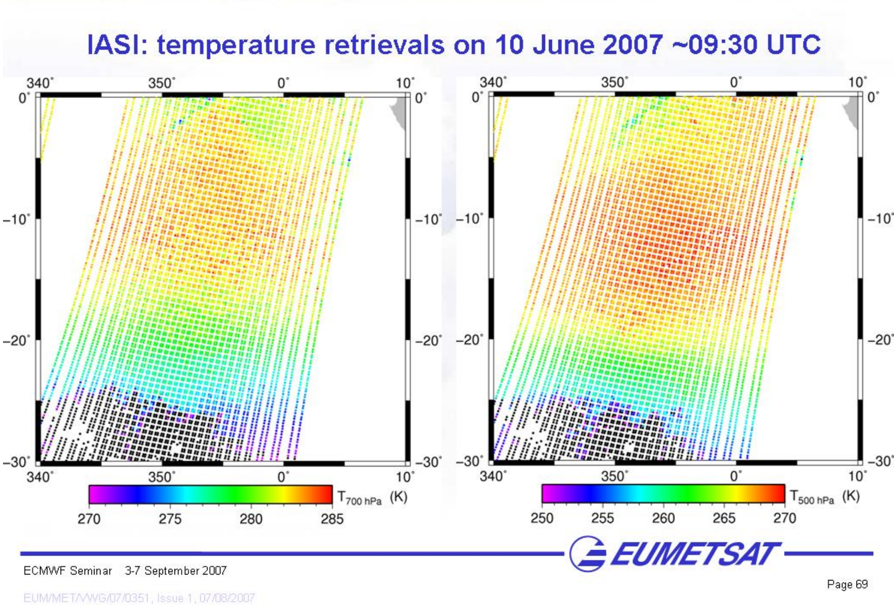
Page 67


JAIVEx: Joint Airborne IASI Validation Experiment
Oklahoma ARM-CART Site Used for IASI Validation
IASI Surface/Cloud Temperature (K)
CART site
IASI nadir Temperature Cross section (K)
IASI nadir H2O Cross section (g/kg)
IASI nadir RH Cross section (%)
raob
drop
Temp (K)
H2O (g/kg)
RH (%)
Altitude (km)
Latitude (deg.)
Longitude (deg.)
EUMETSAT
ECMWF Seminar 3-7 September 2007
EUM/MET/VWG/07/0351, Issue 1, 07/08/2007
Page 68


IASI: temperature retrievals on 10 June 2007 ~09:30 UTC
$T_{700\ hPa}$ (K)
$T_{500\ hPa}$ (K)
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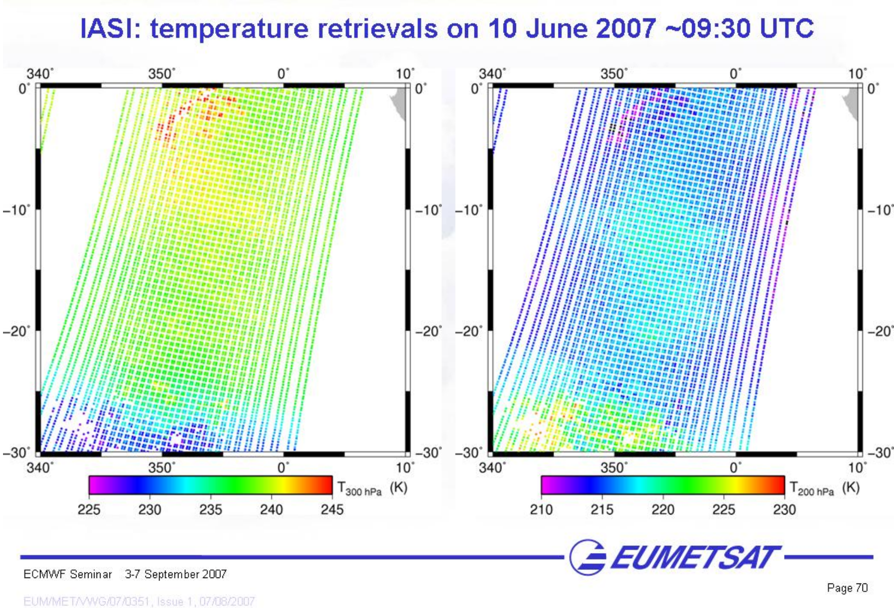
EUM/MET/VWG/07/0351, Issue 1, 07/08/2007
Page 69


IASI: temperature retrievals on 10 June 2007 ~09:30 UTC
$T_{300\ hPa}$ (K)
$T_{200\ hPa}$ (K)
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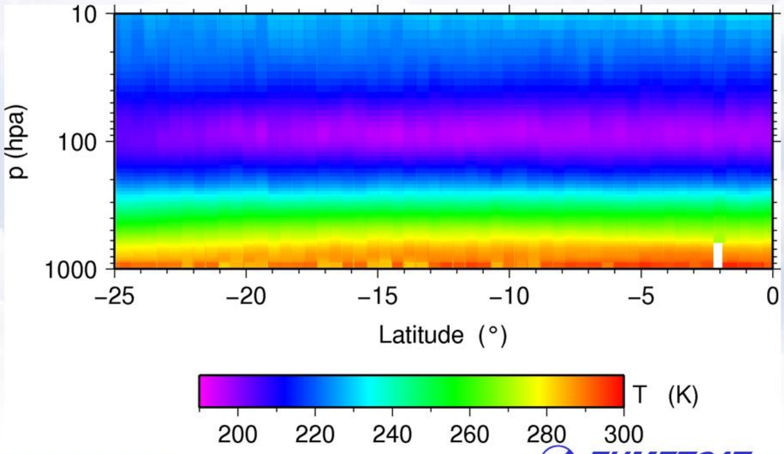
Page 70

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



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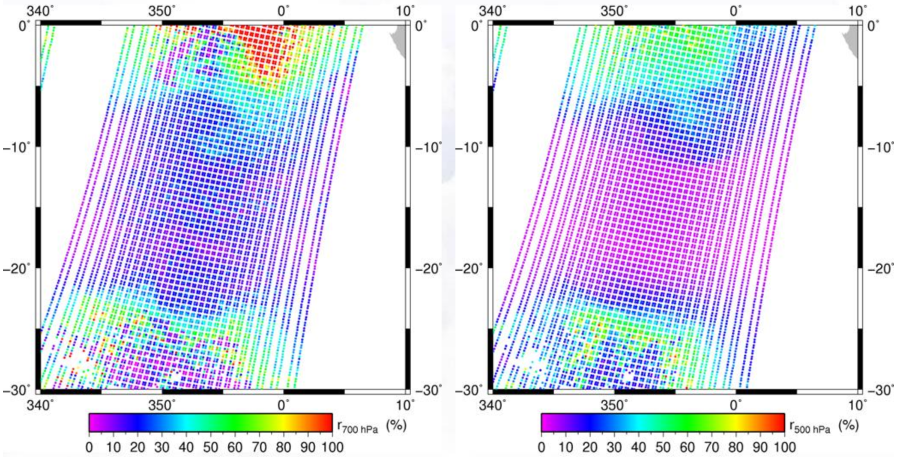
EUM/MET/VWG/07/0351, Issue 1, 07/08/2007

Page 71

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



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Page 72

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

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EUM/MET/VWG/07/0351, Issue 1, 07/08/2007

Page 73

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

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EUM/MET/VWG/07/0351, Issue 1, 07/08/2007

Page 74

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**

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EUM/MET/VWG/07/0351, Issue 1, 07/08/2007

Page 75

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:

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

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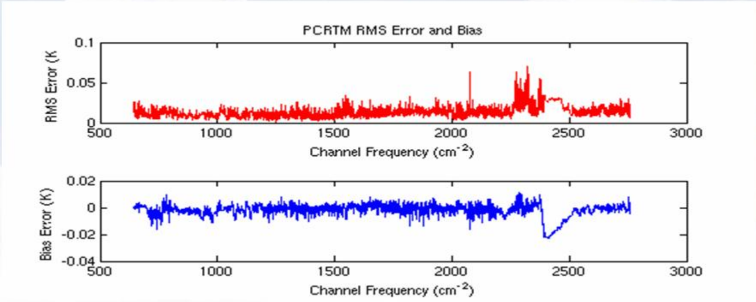
EUM/MET/VWG/07/0351, Issue 1, 07/08/2007

Page 76

PCRTM: Training with LBL-model

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



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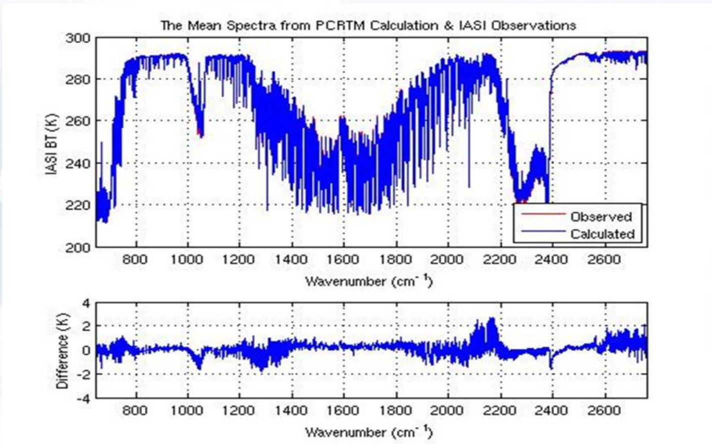
EUM/MET/VWG/07/0351, Issue 1, 07/08/2007

Page 77

PCRTM: validation with ECMWF and IASI data



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EUM/MET/VWG/07/0351, Issue 1, 07/08/2007

Page 78

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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EUM/MET/VWG/07/0351, Issue 1, 07/08/2007

Page 79