First lessons learnt from Metop

Peter Schlüssel

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
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
The Metop Satellite

- 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
Metop: Satellite and Met-Instruments

- AVHRR-3
- IASI
- HIRS-4 (Metop A, B only)
- AMSU-A1
- AMSU-A2
- GOME-2
- ASCAT
- GRAS
- MHS
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 outgassing: 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.
From launch to operational use (3/3)

• Progressive dissemination of data to users
  — Monitoring by NWP centres (ECMWF and Met Office) 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 calibration 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

<table>
<thead>
<tr>
<th>Days from</th>
<th>01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start of SIOV</td>
<td>ICU Switch on (Including NIU &amp; MPU)</td>
</tr>
</tbody>
</table>

ECMWF Seminar 3-7 September 2007

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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 with 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, March 2007
  – IfM/Polarstern: Atlantic Ocean, April/May 2007
  – Met Office/NASA FAAM and WB-57: Golf of Mexico 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
Satellite Application Facilities (SAF)

- SAF on Ozone Monitoring
- SAF on GPS Profiling
- SAF on Climate Monitoring
- SAF on Numerical Weather Prediction
- SAF on Ocean & Sea Ice
- SAF on Land Surface Analysis
- SAF on Hydrology & Water Management
- SAF on Nowcasting & Very Short Range Forecasting

Member State
Cooperating State

Satellite Application Facilities (SAF) consortium leaders
National meteorological service / SAF partner
Global Mission: Provision of global data from Metop and NOAA satellites within 2¼ hours after respective measurements

Local Mission: Real-time data transfer of imaging and sounding instruments to local receiving stations

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

EPS Service

IASI TEC
CNES Toulouse
IASI-Cal/Val and monitoring

UMARF
Central archive

EUMETSAT
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:

Wind vectors vectors in polar regions

CIMSS/Univ. Wisconsin
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: -0.227065 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)**

<table>
<thead>
<tr>
<th>Channel</th>
<th>Spec</th>
<th>Met Office estimate</th>
<th>NOAA-18</th>
<th>Channel</th>
<th>Spec</th>
<th>Met Office estimate</th>
<th>NOAA-18</th>
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<td>0.16</td>
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<td>0.20</td>
<td></td>
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Feedback from Met Office
MHS noise figures (NE\(_\Delta T\) in K)

<table>
<thead>
<tr>
<th>Channel</th>
<th>Spec</th>
<th>EUMETSAT estimate</th>
<th>Met Office estimate</th>
<th>NOAA-18 EUM/ NOAA</th>
<th>AMSU-B EUM/ NOAA</th>
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<tr>
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<td>0.19</td>
<td>0.20</td>
<td>0.21/0.32</td>
<td>0.41/0.40</td>
</tr>
<tr>
<td>2</td>
<td>1.0</td>
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<td>0.37</td>
<td>0.34/0.53</td>
<td>0.80/0.80</td>
</tr>
<tr>
<td>3</td>
<td>1.0</td>
<td>0.52</td>
<td>0.50</td>
<td>0.54/0.50</td>
<td>0.82/0.80</td>
</tr>
<tr>
<td>4</td>
<td>1.0</td>
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<td>0.41</td>
<td>0.40/0.41</td>
<td>0.75/0.75</td>
</tr>
<tr>
<td>5</td>
<td>1.0</td>
<td>0.36</td>
<td>0.34</td>
<td>0.55/0.55</td>
<td>0.80/0.80</td>
</tr>
</tbody>
</table>
• ASCAT: Advanced Scatterometer
LEVEL 1b: Sigma0-triplets as RGB image

LEVEL 2: surface wind (ocean)

LEVEL 2: soil moisture (land)
ASCAT

Normalised backscatter coefficients ($\sigma_0$)
ASCAT: first comparisons by ECMWF

H. Hersbach, 2006
• GOME-2: Global Ozone Monitoring Experiment 2
First GOME-2 ozone columnar contents

Loyola, 2007
First GOME-2 NO$_2$ columnar contents

Loyola, 2007

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

$10^{16}$ mol cm$^{-2}$
GRAS
GAVA antenna

Global Receiver for Atmospheric Sounding
GRAS: Reception of GPS signals and its atmospheric diffraction

GRAS (setting) at 67.0N, 20.2W

<table>
<thead>
<tr>
<th>Geopotential Height [km]</th>
<th>Temperature [K]</th>
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<tbody>
<tr>
<td>40</td>
<td>300</td>
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<tr>
<td>35</td>
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</tr>
<tr>
<td>15</td>
<td>50</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
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</table>

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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, O₃, CO, CO₂, CH₄, N₂O, ...
IASI FM-2: Radiometric noise

![Graph showing IASI FM-2 radiometric noise with bands B1, B2, and B3 highlighted. The graph includes markers for various chemical species such as O3, H2O, Temp (CO2), CH4, N2O, SO2, and CO, with specific temperature markers at 280 K.]
Scan patterns of the instruments

IASI
AMSU-A
MHS
HIRS/4
AVHRR/3
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
Comparisons of simulated and measured spectra
Comparisons of simulated and measured spectra

![Graphs showing comparisons of simulated and measured spectra](image-url)
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:
  - Approximations necessary for fast calculations
  - Insufficient knowledge of spectroscopic data
  - Erroneous input data
- Systematic fit of models to IASI measurements
Discrimination of ice and water clouds

![Graph showing the 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 $\mathrm{N}_2\mathrm{O}$, $\mathrm{CO}$, $\mathrm{CH}_4$, $\mathrm{CO}_2$
  - 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 parameters 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

![Graphs showing comparison between ECMWF and IASI L2](image-url)
JAIVEx: Joint Airborne IASI Validation Experiment

Oklahoma ARM-CART Site Used for IASI Validation
IASI: temperature retrievals on 10 June 2007 ~09:30 UTC

T_{700\,hPa}\,(K)

T_{500\,hPa}\,(K)
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 ($R$)

$$\bar{Y} = U \times \bar{R}^{\text{mono}}$$

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

- Relationship between EOF scores and measured radiances:

$$R^{\text{chan}}_i = \frac{\sum_{k=1}^{N} \phi_k R^{\text{mono}}_k}{\sum_{k=1}^{N} \phi_k}; \quad \bar{Y} = U^T \times \bar{R}^{\text{chan}}$$

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

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

The Mean Spectra from PCRTM Calculation & IASI Observations

Observed vs Calculated

Difference (K)

Wavenumber (cm⁻¹)
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

<table>
<thead>
<tr>
<th>Variable</th>
<th>Radiance/state vector: dimensions</th>
<th>EOF-space: dimensions</th>
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<tbody>
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<td>Y</td>
<td>8461</td>
<td>100</td>
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<tr>
<td>X</td>
<td>&gt;100</td>
<td>50</td>
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<tr>
<td>K</td>
<td>&gt; 8461x100</td>
<td>100x50</td>
</tr>
<tr>
<td>(S_y^{-1})</td>
<td>8461x8461</td>
<td>100x100</td>
</tr>
<tr>
<td>(S_a)</td>
<td>&gt; 100x100</td>
<td>50x50</td>
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Calculation of \(K\) and \(Y\):
- \(~2\) s
- \(~0.1\) s