A study on operational atmospheric chemistry monitoring missions ("CAPACITY study")

Jörg Langen, ESA
Scope of the CAPACITY study

- Chemical, dynamic and radiative coupling between air quality, climate change and stratospheric ozone
- Governments have been advised to optimise emission regulation strategies by combined consideration of air quality and climate
- Overlapping observational requirements
- Common programmatic framework for all three issues

consideration of all “operational” applications of atmospheric composition sounding
Objectives of the CAPACITY study

- User requirements for operational atmospheric composition sounding
- Quantitative observational requirements
- Possible contributions of current and planned missions
- Mission concepts and instrument requirements for future missions
- Performance assessment with respect to user requirements

Reference time frame: 2010-2020 (Metop/EPS operational)
Study consortium

Prime: KNMI (H. Kelder)

Core team:
- Rutherford-Appleton Lab (B. Kerridge)
- Univ. Leicester (P. Monks, J. Remedios)
- Univ. Bremen (H. Bovensmann)
- EADS-Astrium (R. Mager)
- Alcatel Space (H. Sassier)

Consultants:
- Requirements – WMO, JRC, 5 weather and environmental agencies, Eurocontrol, 11 research institutes and universities
- Space instrumentation – 10 research institutes and universities, 1 company
- Ground instrumentation – 1 research institute
Sources of user and observational requirements

- IGOS-IGACO Theme report
- EU GMES-GATO report
- EU FP projects, e.g. Create-Daedalus, Evergreen
- Eumetsat user consultation in the frame of MTG
- Environment and climate protection protocols, directives etc. (EU, international)
- GCOS implementation plan, WCRP-SPARC long-term observation requirements
- GMES service element PROMOTE
- ESA studies on CO₂ monitoring
- ESA study on atmospheric chemistry observation requirements (research)
- CAPACITY workshop Jan. ’04

... many useful inputs, but ...

Air Quality Remote Sensing from Space, Boulder, 21-23 Feb 2006
... we need a set of requirements ...

- for each environmental theme
- for each application type
- self-consistent
- sufficiently complete to perform trade-offs between space mission concepts
- following an integrated observation strategy (IGACO) considering ground, airborne and space observations and assimilation / models

→ comprehensive set of observational requirements was established.
## Environmental themes, data usage, applications

<table>
<thead>
<tr>
<th>Environmental Theme</th>
<th>Ozone Layer &amp; Surface UV radiation</th>
<th>Air Quality</th>
<th>Climate</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Data usage</strong></td>
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<tr>
<td><strong>Protocols</strong></td>
<td>UNEP Vienna Convention; Montreal and subs. Protocols CFC emission verification Stratospheric ozone, halogen and surface UV distribution and trend monitoring</td>
<td>UN/ECE CLRTAP; EMEP / Göteborg Protocol; EC directives EAP / CAFE AQ emission verification AQ distribution and trend monitoring</td>
<td>UNFCCC Rio Convention; Kyoto Protocol; Climate policy EU GHG and aerosol emission verification GHG/aerosol distribution and trend monitoring</td>
</tr>
<tr>
<td><strong>Services</strong></td>
<td>Stratospheric composition and surface UV forecast NWP assimilation and (re-)analysis</td>
<td>Local Air Quality (BL); Health warnings (BL)</td>
<td>NWP assimilation and (re-)analysis Climate monitoring Climate model validation</td>
</tr>
<tr>
<td><strong>Assessment</strong></td>
<td>Long-term global data records WMO Ozone assessments Stratospheric chemistry and transport processes; UV radiative transport processes Halogen source attribution UV health &amp; biological effects</td>
<td>Long-range transport processes AQ source attribution AQ Health and safety effects</td>
<td>Forcing agents source attribution Socio-economic climate effects</td>
</tr>
</tbody>
</table>

### Requirements per application

**Michiel van Weele, Wed 15.45h**
Measurement strategy - example: climate protocol monitoring

Role of Satellite Measurements

- Concentration monitoring for inverse modeling of CH$_4$, CO$_2$, CO and NO$_2$ emissions
- Global concentration distributions of the mentioned gases, O$_3$ and aerosols

Role of Surface network

- Greenhouse gases trend monitoring (CO$_2$, CH$_4$, N$_2$O, SF$_6$, CF$_4$, HFCs)
- Weekly surface concentrations and total columns from a representative network
- Validation of satellite measurements
- Concentration monitoring for inverse modeling of CH$_4$, CO$_2$, CO and NO$_2$ emissions
- Tropospheric O$_3$: sondes, lidar and surface data
- Tropospheric aerosol optical depth and aerosol absorption optical depth
- Trend monitoring for ozone depleting substances with climate forcing: (H)CFCs

Auxiliary data

- Meteorology from NWP centers including surface data
- Emission inventories and estimates on sinks

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<tr>
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</table>
### Observational requirements – example: AQ NRT satellite

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Driver</th>
<th>Height Range</th>
<th>Horizontal resolution (km)</th>
<th>Vertical resolution (km)</th>
<th>Revisit Time (hours)</th>
<th>Uncertainty</th>
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<tbody>
<tr>
<td><strong>O3</strong></td>
<td>PBL</td>
<td>5 / 20</td>
<td>0.5 / 2</td>
<td>10%</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>FT</td>
<td>5 / 20</td>
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<td>5 / 2</td>
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<tr>
<td></td>
<td></td>
<td>50 / 100</td>
<td>-</td>
<td>25%</td>
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<tr>
<td><strong>NO2</strong></td>
<td>FT</td>
<td>5 / 20</td>
<td>0.5 / 2</td>
<td>10%</td>
<td>1.3 x 15 molec cm⁻²</td>
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<td>5 / 20</td>
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<td>5 / 2</td>
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<tr>
<td><strong>CO</strong></td>
<td>PBL</td>
<td>5 / 20</td>
<td>0.5 / 2</td>
<td>20%</td>
<td>1.3 x 15 molec cm⁻²</td>
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<tr>
<td></td>
<td>FT</td>
<td>5 / 20</td>
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<tr>
<td><strong>Aerosol OD</strong></td>
<td>PBL</td>
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<td>0.5 / 2</td>
<td>0.05</td>
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<td>5 / 20</td>
<td>-</td>
<td>0.05</td>
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<tr>
<td><strong>Aerosol Type</strong></td>
<td>PBL</td>
<td>5 / 20</td>
<td>0.5 / 2</td>
<td>&lt; 10% mis-assignments</td>
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<tr>
<td></td>
<td>FT</td>
<td>5 / 20</td>
<td>-</td>
<td>&lt; 10% mis-assignments</td>
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<tr>
<td><strong>H2O</strong></td>
<td>PBL</td>
<td>5 / 20</td>
<td>0.5 / 2</td>
<td>10%</td>
<td>1.3 x 15 molec cm⁻²</td>
<td></td>
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<tr>
<td></td>
<td>FT</td>
<td>5 / 20</td>
<td>-</td>
<td>5 / 2</td>
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<tr>
<td><strong>SO2</strong></td>
<td>PBL</td>
<td>5 / 20</td>
<td>0.5 / 2</td>
<td>10%</td>
<td>1.3 x 15 molec cm⁻²</td>
<td></td>
</tr>
<tr>
<td></td>
<td>FT</td>
<td>5 / 20</td>
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<tr>
<td><strong>CH2O</strong></td>
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<tr>
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<td>5 / 20</td>
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<tr>
<td><strong>HNO3</strong></td>
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<td>0.5 / 2</td>
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<tr>
<td></td>
<td>FT</td>
<td>5 / 20</td>
<td>-</td>
<td>5 / 2</td>
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<tr>
<td><strong>N2O5 (night)</strong></td>
<td>PBL</td>
<td>5 / 20</td>
<td>0.5 / 2</td>
<td>1.3 x 15 molec cm⁻²</td>
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<td>FT</td>
<td>5 / 20</td>
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<tr>
<td><strong>PAN</strong></td>
<td>PBL</td>
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<td>&lt; 10% mis-assignments</td>
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<td>5 / 20</td>
<td>-</td>
<td>&lt; 10% mis-assignments</td>
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<tr>
<td><strong>Spectral UV surface albedo</strong></td>
<td>Surface</td>
<td>5 / 20</td>
<td>24 / 24*</td>
<td>1.0</td>
<td>0.1</td>
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</tbody>
</table>
Geographical coverage requirements

Ozone Layer & Surface UV radiation

<table>
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<td>A3</td>
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<td>C3</td>
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global

Air Quality

threshold: Europe + surrounding areas (e.g. monitoring of EC directives and national AQ legislation, short-term air quality forecast)

target: global (monitoring, assessment and forecast of global air quality, the oxidising capacity, and the quantification of continental in/outflow)

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<tr>
<td>3</td>
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</table>

Climate
global
### Capacity Study

**Assessment of existing and planned missions - example: Ozone NRT**

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Data</th>
<th>Driver</th>
<th>Height Range (km)</th>
<th>Horizontal resolution (km)</th>
<th>Vertical resolution (km)</th>
<th>Revisit Time (hours)</th>
<th>Uncertainty</th>
<th>Type of Observations: Ozone Layer Near-Real Time Data Satellite</th>
</tr>
</thead>
<tbody>
<tr>
<td>O3</td>
<td>Ozone and UV Forecast</td>
<td>UT</td>
<td>50 / 100</td>
<td>0.5</td>
<td>1</td>
<td>5 / 24 / 3</td>
<td>20%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>LS</td>
<td>80 / 100</td>
<td>0.5 / 3</td>
<td>1</td>
<td>5 / 24 / 3</td>
<td>20%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>MS</td>
<td>100 / 200</td>
<td>0.5 / 3</td>
<td>1</td>
<td>6 / 24 / 3</td>
<td>20%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>US+M</td>
<td>100 / 200</td>
<td>3 / 5</td>
<td>12 / 24 / 7</td>
<td>20%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Troph. column</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6 / 24 / 3</td>
<td>20%</td>
<td></td>
</tr>
<tr>
<td>Total column</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6 / 24 / 3</td>
<td>5%</td>
<td></td>
</tr>
<tr>
<td>Spectral UV Surf. Alb.</td>
<td>UV Forecast</td>
<td>Surface</td>
<td>10 / 50</td>
<td></td>
<td></td>
<td>6 / 24 / 3</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Spectral UV Sol. Irr.</td>
<td>UV Forecast</td>
<td>Top of Atmosphere</td>
<td></td>
<td></td>
<td></td>
<td>Daily / Monthly</td>
<td>2%</td>
<td></td>
</tr>
<tr>
<td>UV Aerosol OD</td>
<td>UV Forecast</td>
<td>Total column</td>
<td>10 / 50</td>
<td></td>
<td></td>
<td>6 / 24 / 3</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>UV Aerosol Abs. OD</td>
<td>UV Forecast</td>
<td>Total column</td>
<td>10 / 50</td>
<td></td>
<td></td>
<td>6 / 24 / 3</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>Strat. Aerosol OD</td>
<td>Ozone loss</td>
<td>LS</td>
<td>50 / 100</td>
<td>0.5 / 2</td>
<td>6 / 24 / 3</td>
<td>0.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>MS</td>
<td>50 / 100</td>
<td>1 / 3</td>
<td>12 / 24 / 7</td>
<td>0.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stratosphere</td>
<td>50 / 200</td>
<td></td>
<td></td>
<td>6 / 24 / 7</td>
<td>0.05</td>
<td></td>
</tr>
</tbody>
</table>

**Colours indicate instruments; patterns indicate fulfilment of requirements.**

Air Quality Remote Sensing from Space, Boulder, 21-23 Feb 2006
Assessment of existing and planned missions – quick summary

Current status of observational system in 2010-2020:

<table>
<thead>
<tr>
<th>MetOp / EPS</th>
<th>GOME-2, IASI</th>
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<tbody>
<tr>
<td>NPOESS</td>
<td>OMPS, CRIS</td>
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</table>

**GOME-2 and OMPS**
- designed for stratospheric ozone monitoring
- considered appropriate for this purpose
- some contribution to NWP
- **contributions to tropospheric applications very limited**, due to insufficient temporal sampling (~ 1/week/geo-location cloud-free) and too coarse horizontal resolution

**IASI and CRIS**
- main products: T, greenhouse gases (H$_2$O, O$_3$, CH$_4$, N$_2$O) and CO
- vertical profiles of H$_2$O; vertical resolution for tropospheric O$_3$, CO
- sensitivity decreasing towards planetary boundary layer (main interest)
Main gaps in current / planned operational system

- Climate gases (CO$_2$, CH$_4$ and CO) and aerosol monitoring with sensitivity to the PBL
- High vertical resolution measurements in the UT/LS region for ozone and climate applications
- High temporal/spatial resolution space-based measurements of tropospheric (PBL) composition for application to air quality

in line with IGACO findings
Mission concept for climate protocol monitoring applications (lower troposphere)

**System:** sun-synchronous LEO platform

**Instrumentation:** UV-vis-SWIR spectrometer for O$_3$, NO$_2$, CH$_4$, CO, aerosol

Mission concept for ozone and climate applications in the UTLS

**System:** sun-synchronous LEO platform with a limb-sounder, formation flying with Metop or other new mission with nadir-viewing instruments in order to support their tropospheric data products

**Instrumentation options:**
either mm-wave (MASTER derivative) or mid-IR (AMIPAS derivative)

Mission concept for air quality

**Instrumentation options:**
1) combined solar backscatter and thermal IR sounding
2) solar backscatter only
Mission concept for air quality - system options

Driving requirements (protocol monitoring, forecast):
Revisit time 0.5 – 2 h  Spatial resolution 5 – 20km

System options:
A  1 geostationary satellite to satisfy spatio-temporal sampling requirements over Europe, and
   1 LEO satellite in sun-synchronous orbit for global pollution transport (Convention on long-range transport of air pollutants, medium-range forecast)
B  a constellation of 3 satellites in inclined LEO to satisfy spatio-temporal sampling requirements globally at mid-latitudes, with reduced sampling at low latitudes
C  1 satellite in sun-synchronous LEO, with local time defined to complement Metop and NPOESS diurnal sampling (afternoon orbit)
How to reach 2h revisit time at mid-latitudes with LEO constellation?

1. Increase swath width by elevating orbit altitude
   - 2h revisit time with 3 sun-synchronous satellites implies 3000km orbit, at top of proton radiation level
   - 3.5h revisit time at latitudes > 30° realistic with 3 sun-synchronous satellites, 900km orbit.
   → requirement not fulfilled.

2. Use inclined orbit (non sun-synchronous)
   - orbit more efficient at inhabited latitude ranges
   - polar regions not covered
   - 3 satellites at 900km provide 1.7 hours revisit time at mid latitudes (~35°… 65°) and reduced sampling at lower latitudes.
   → possible solution. High orbit desirable.
3 satellites at 900km, 125° inclination (two consecutive orbits)
Conclusions from CAPACITY Study for GMES Sentinels 4 and 5
Conclusions for Sentinels 4 and 5

1. **Implement** 1 LEO satellite with UV-VIS-SWIR payload for global air quality and climate protocol monitoring as soon as possible

2. Perform trade-off between GEO+LEO and LEO constellation in inclined orbit, and complete implementation of air quality & climate protocol monitoring mission

3. Consolidate choice and requirements of instrument for UTLS mission for climate and ozone NRT and assessment applications, and implement the mission
1. Implement 1 LEO satellite with UV-VIS-SWIR payload for global air quality and climate protocol monitoring as soon as possible

- air quality applications are developing quickly, OMI/Aura demonstrating space contribution, continuity issue arising at its end of life
- climate protocol monitoring high on the agenda – continuity of SCIAMACHY CH$_4$ measurements, aerosol
- technology well demonstrated in space (GOME, SCIAMACHY, OMI; also TOMS, SBUV) – no technology specific failures
- 1 LEO platform is common to all air quality system options; only orbit-specific aspects need separate consideration (e.g. stray light, solar generator, radiation)
- orbit trade-off result needed after phase A

This mission will provide continuity to existing global missions with better spatial resolution.
2. Perform trade-off between GEO+LEO and LEO constellation in inclined orbit, and complete implementation of air quality & climate protocol monitoring mission

Trade-off (during phases 0 and A) involves

- Level 2 error budgets on individual soundings
- spatio-temporal sampling under consideration of cloud
- end-user performance analysis
- maturity, cost and risk

Implementation (assuming one LEO implemented via 1.):

launch of either GEO or remaining two inclined LEO platforms.

This mission will enhance the previous one to provide high temporal resolution, either regional (GEO) or quasi-global (LEO).
3. Consolidate choice and requirements of instrument for UTLS mission for climate and ozone NRT and assessment applications, and implement the mission

- monitoring of ozone, climate and stratosphere-troposphere exchange
- NRT applications now in demonstration phase (MIPAS, Aura-MLS), new hypotheses on stratospheric precursors of weather patterns
- support to tropospheric missions via vertical resolution
- choice of instrument type (mm-wave or mid-IR limb-sounder) depends on priorities of applications
- prototype instrument specifications exist – need to be tailored towards operational applications
The Link to EUMETSAT
Atmospheric chemistry applications depend on accurate dynamics fields, and some of them are natural extensions of NWP.

Eumetsat has already integrated a basic set of atmospheric chemistry observations on Metop / EPS (GOME-2, IASI).

Eumetsat user consultation for MTG and post-EPS in cooperation with ESA, ESA performing phase 0 system studies.

UV-VIS sounder and IR sounder with chemistry capabilities being considered for MTG – implementation unclear.

Application experts group for atmospheric chemistry working on post-EPS observational requirements, on basis of ESA Capacity study results.

Eumetsat “natural” agency for operation of GMES sentinels 4 and 5 – precise arrangement between EC, ESA and Eumetsat to be defined.
Considerations for post-EPS timeframe
(seen as extension of CAPACITY requirements)

- air quality / climate protocol monitoring mission needs nadir-viewing thermal IR sounder (IASI replacement)

- **Global total ozone** data needed, options:
  - UV-VIS nadir sounder on LEO AQ mission in sun-synchronous orbit, or on any other platform in polar orbit;
  - an alternative might be
  - mm-wave or thermal IR limb-sounder on UTLS mission.