# Future European Air Quality Satellite Missions

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# Global Monitoring for Environment and Security (GMES) – the European contribution to GEOSS

## Services Component – led by EC

- **Produces information services in response to European policy priorities in environment and security**
- Relies on data from in-situ and space component

## In-situ component – led by EEA

- Observations mostly within national responsibility, with coordination at European level

## Space Component – led by ESA

- Sentinels - EO missions developed specifically for GMES
- Contributing Missions - EO missions built for purposes other than GMES but offering part of their capacity to GMES

# GMES dedicated missions: Sentinels

**Sentinel 1 – SAR imaging**

All weather, day/night applications, interferometry

2011

**Sentinel 2 – Multispectral imaging**

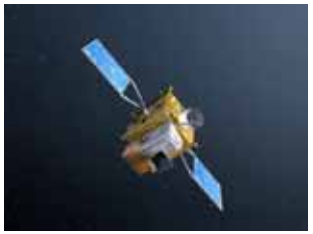
Land applications: urban, forest, agriculture,.. Continuity of Landsat, SPOT

2012

**Sentinel 3 – Ocean and global land monitoring**

Wide-swath ocean color, vegetation, sea/land surface temperature, altimetry

2012



**Sentinel 4 – Geostationary atmospheric**

Atmospheric composition monitoring

2017+

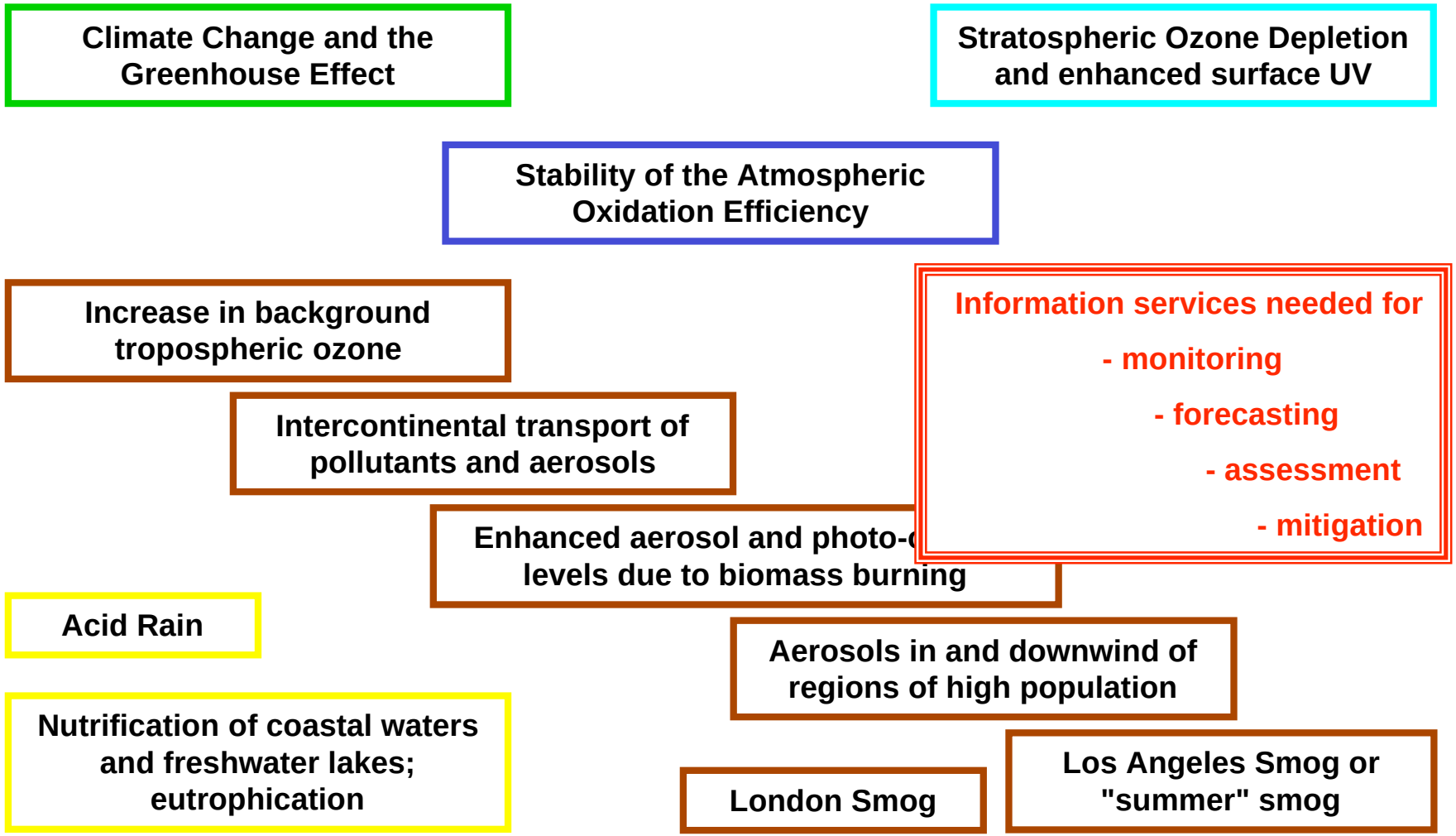
**Sentinel 5 – Low-Earth orbit atmospheric**

Atmospheric composition monitoring

(S5 Precursor launch in 2014)

2019+

# Environmental issues of changing atmospheric composition



# Sources for Sentinel 4 and 5 mission requirements

***EU documents on GMES Atmospheric Service (GAS)***

- GAS Orientation paper and workshop report, 12/2006
- FP7 Cooperation Work Programme Space, 6/2007
- GAS IG Report and WG4 Report and Summary, 2008

***GAS precursor projects***

- FP7 Integrated Project GEMS
- GMES Service Element PROMOTE

***Environment and climate protection protocols***

- Vienna convention – Montreal protocol
- UNFCCC – Kyoto protocol
- UNECE – CLRTAP, EU directives

***Related work on observation requirements***

- IGOS-IGACO Theme report
- GCOS implementation plan
- WCRP-SPARC long-term observation requirements
- EU GMES-GATO report
- EU FP projects, e.g. Create-Daedalus, Evergreen
- Eumetsat user consultation and studies in the frame of MTG / post-EPS
- ESA studies on $CO_2$ monitoring
- ESA study on atmospheric chemistry observation requirements
- **ESA study dedicated to S4&5 requirements (“CAPACITY”) incl. user workshop**
- **ESA study on radiance requirements (“CAMELOT”), ongoing**

## Sentinels 4&5 are to support GMES atmospheric services:

### *Core services*

- standard operational products and information services providing direct support to European policy and information on global issues
- Sustained public funding (EU & Member States)
- Pilot service “GMES Atmospheric Service (GAS)”: EU FP7 activity “MACC” to start in June
- precursor / development activities: GEMS (EU FP6 Integrated Project), PROMOTE (ESA GMES Service Element)

### *Downstream services*

- targeted services that address specific user requirements, or trans-national, national, regional or local problems
- EU not directly driving the service and not responsible for service requirements
- use core service data as input
- call to be issued
- precursor / development activities: PROMOTE, national developments

## Core Service components

### *Air quality*

- integrated global and European air quality analysis;
- integrated global and European air quality forecast;
- historic records of Global and European atmospheric composition.

### *Climate forcing*

- improved and sustained monitoring of the state of the climate system (surface and upper air meteorology and composition) and its variability;
- integrated global, European and regional concentration fields of key greenhouse gases ($CO_2$, $CH_4$ and related tracers) enabling determination of sources and sinks.

### *Stratospheric ozone and solar radiation*

- improved and sustained monitoring of the current status and trends in stratospheric ozone depletion and ozone depleting gases;
- routine provision of updated ozone, UV and solar radiation maps and forecasts;
- historic European UV and solar radiation records and mapping.

# Examples of downstream services

## *Air quality*

• local air quality forecasts, e.g. as input to traffic regulation

• Improved air-quality-related alerts and forecasts for health services supporting vulnerable communities (COPD, asthma, pollen-induced allergies)

• daily compliance with air-quality legislation (threshold exceedance warning)

• support to development of effective air pollution abatement measures through proper apportionment of sources and assessment of impacts (human exposure) etc.

• forecasts for extreme events involving the combined effects of heat stress, high UV-B exposure and poor air quality.

## *Climate change*

• information for quick response to extreme weather events and natural catastrophes

• identification, assessment and monitoring of regional/local sources and sinks of greenhouse gases and pollutants and related tracers in support of emission and sink verification and mitigation policy.

## *Stratospheric ozone and solar radiation*

• surface UV-radiation monitoring and forecasting;

• personalized skin-type specific UV information

# Mapping of services to Level 2 data products (simplified)

**GEMS:**
prototype core service

**PROMOTE:**
prototype downstream services

X – target product
x – auxiliary product

| Level -2 data product | Services (as introduced in chapter 3) | | | | |
|---|---|---|---|---|---|
| | GEMS - GRG | GEMS - GRG | GEMS - GRG and -RAQ | GEMS - GHG | GEMS - Aerosol |
| | Promote -Strat. $O_3$ | Promote - UV | Promote - AQ | Promote - Climate | Promote - Volcanic |
| Stratospheric ozone ($O_3$) | **X** | X | X | | |
| Tropospheric ozone ($O_3$) | | **X** | **X** | | |
| Sulphur dioxide ($SO_2$) | | | **X** | | **X** |
| Volcanic $SO_2$ | | | **X** | | **X** |
| Total ozone ($O_3$) | **X** | **X** | | | |
| Aerosol | | | **X** | | **X** |
| Formaldehyde ($CH_2O$) | | | **X** | | |
| Bromine monoxide (BrO) | **X** | | | | |
| aerosol absorption | X | X | **X** | X | **X** |
| Nitrogen dioxide ($NO_2$) | | | **X** | | |
| Glyoxal (CHOCHO) | | | **X** | | |
| Water vapour ($H_2O$) | | | | **X** | |
| Methane ($CH_4$) | | | | **X** | |
| Carbon monoxide (CO) | | | **X** | **X** | |
| Nitric acid ($HNO_3$) | **X** | | **X** | | |

# Environmental themes, data usage, services

| Environmental Theme / Data usage | Ozone Layer & Surface UV radiation **A** | Air Quality **B** | Climate **C** |
|---|---|---|---|
| Protocol monitoring **1** | UNEP Vienna Convention; Montreal and subs. Protocols<br>CFC emission verification<br>Stratospheric ozone, halogen and surface UV distribution and trend monitoring **A1** | UN/ECE CLRTAP; EMEP / Göteborg Protocol; EC directives EAP / CAFE<br>AQ emission verification<br>AQ distribution and trend monitoring **B1** | UNFCCC Rio Convention; Kyoto Protocol; Climate policy EU<br>GHG and aerosol emission verification<br>GHG/aerosol distribution and trend monitoring **C1** |
| Near real time services **2** | Stratospheric composition and surface UV forecast<br>NWP assimilation and (re-) analysis **A2** | Local Air Quality (BL); Health warnings (BL)<br>Chemical Weather (BL/FT)<br>Aviation route (FT) **B2** | NWP assimilation and (re-) analysis<br>Climate monitoring<br>Climate model validation **C2** |
| Assessment (lower priority for operational mission) **3** | Long-term global data records<br>WMO Ozone assessments<br>Stratospheric chemistry and transport processes;<br>UV radiative transport processes **A3**<br>Halogen source attribution<br>UV health & biological effects | Long-term global, regional, and local data records<br>UNEP, EEA assessments<br>Regional & local boundary layer AQ processes;<br>Tropospheric chemistry and long-range transport processes **B3**<br>AQ source attribution<br>AQ Health and safety effects | Long-term global data records<br>IPCC assessments<br>Earth System, climate, rad. forcing processes; UTLS transport-chemistry processes **C3**<br>Forcing agents source attribution<br>Socio-economic climate effects |

## Comprehensive set of related observational requirements established in ESA “CAPACITY” study

- 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
- using information from existing reviews and ongoing activities

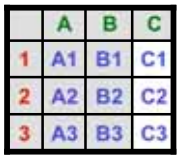
# Observational requirements – example: AQ NRT satellite

**B2-S**

Theme: **Air Quality**
Category: **Near-Real Time Data**
Type of Observations: **Satellite**

| Data Product \ Requirement | Driver | Height Range | Horizontal resolution (km) | Vertical resolution (km) | Revisit Time (hours) | Uncertainty |
|---|---|---|---|---|---|---|
| O3 | Air Quality Forecast; UV actinic fluxes | PBL | 5 / 20 | -- | 0.5 / 2 | 10% |
| | | FT | 5 / 50 | 1 / 3 | 0.5 / 2 | 20% |
| | | Tropospheric Column | 5 / 20 | -- | 0.5 / 2 | 25% |
| | | Total Column | 50 / 100 | -- | 12 / 24*3 | 5% |
| NO2 | Air Quality Forecast | PBL | 5 / 20 | -- | 0.5 / 2 | 10% |
| | | FT | 5 / 50 | 1 / 3 | 0.5 / 2 | 20% |
| | | Tropospheric Column | 5 / 20 | -- | 0.5 / 2 | 1.3e15 molec cm-2 |
| | | Total Column | 5 / 20 | -- | 0.5 / 2 | 1.3e15 molec cm-2 |
| CO | Air Quality Forecast | PBL | 5 / 20 | -- | 0.5 / 2 | 20% |
| | | FT | 5 / 50 | 1 / 3 | 0.5 / 2 | 20% |
| | | Ttropospheric Column | 5 / 20 | -- | 0.5 / 2 | 25% |
| | | Total Column | 5 / 20 | -- | 0.5 / 2 | 25% |
| Aerosol OD | Air Quality Forecast; UV actinic fluxes | PBL | 5 / 20 | -- | 0.5 / 2 | 0.05 |
| | | FT | 5 / 50 | -- | 0.5 / 2 | 0.05 |
| | | Ttropospheric Column | 5 / 20 | -- | 0.5 / 2 | 0.05 |
| | | Total Column | 5 / 20 | -- | 0.5 / 2 | 0.05 |
| Aerosol Type | Air Quality Forecast | PBL | 5 / 20 | -- | 0.5 / 2 | < 10% mis-assignments |
| | | FT | 5 / 50 | -- | 0.5 / 2 | < 10% mis-assignments |
| | | Ttropospheric Column | 5 / 20 | -- | 0.5 / 2 | < 10% mis-assignments |
| | | Total Column | 5 / 20 | -- | 0.5 / 2 | < 10% mis-assignments |
| H2O | Air Quality Forecast | PBL | 5 / 20 | -- | 0.5 / 2 | 10% |
| | | FT | 5 / 50 | 1 / 3 | 0.5 / 2 | 20% |
| | | Tropospheric Column | 5 / 20 | -- | 0.5 / 2 | 10% |
| | | Total Column | 5 / 20 | -- | 0.5 / 2 | 10% |
| SO2 | Air Quality Forecast | PBL | 5 / 20 | -- | 0.5 / 2 | 20% |
| | | FT | 5 / 50 | 1 / 3 | 0.5 / 2 | 20% |
| | | Tropospheric Column | 5 / 20 | -- | 0.5 / 2 | 1.3e15 molec cm-2 |
| | | Total Column | 5 / 20 | -- | 0.5 / 2 | 1.3e15 molec cm-2 |
| CH2O | Air Quality Forecast | PBL | 5 / 20 | -- | 0.5 / 2 | 20% |
| | | FT | 5 / 50 | 1 / 3 | 0.5 / 2 | 20% |
| | | Tropospheric Column | 5 / 20 | -- | 0.5 / 2 | |
| | | Total Column | 5 / 20 | -- | 0.5 / 2 | |
| HNO3 | Air Quality Forecast | PBL | 5 / 20 | -- | 0.5 / 2 | |
| | | FT | 5 / 50 | 1 / 3 | 0.5 / 2 | |
| | | Tropospheric Column | 5 / 20 | -- | 0.5 / 2 | |
| | | Total Column | 5 / 20 | -- | 0.5 / 2 | |
| N2O5 (night) | Air Quality Forecast | PBL | 5 / 20 | -- | 0.5 / 2 | |
| | | FT | 5 / 50 | 1 / 3 | 0.5 / 2 | |
| | | Tropospheric Column | 5 / 20 | -- | 0.5 / 2 | |
| | | Total Column | 5 / 20 | -- | 0.5 / 2 | |
| PAN | Air Quality Forecast | PBL | 5 / 20 | -- | 0.5 / 2 | |
| | | FT | 5 / 50 | 1 / 3 | 0.5 / 2 | |
| | | Tropospheric Column | 5 / 20 | -- | 0.5 / 2 | |
| | | Total Column | 5 / 20 | -- | 0.5 / 2 | |
| Spectral UV surface albedo | UV actinic fluxes | Surface | 5 / 20 | -- | 24 / 24*3 | |

# Geographical coverage requirements

| | | |
|---|---|---|
| **Ozone Layer & Surface UV radiation** |   | **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) |
| **Climate** |   | **global** |

## Assessment of existing and planned missions (1/2)

### A. Research missions

Envisat, Aura, Odin, Scisat, Mopitt, Gosat – all ongoing

- Wealth of data for science
- Advanced stratospheric component
- Pathfinders for tropospheric applications

Main deficiencies:

- Temporal resolution, horizontal sampling / coverage in nadir
- Vertical resolution in limb

**All expected to stop ≤ 2014, no definitive new plans.**

## Assessment of existing and planned missions (2/2)

### B. Operational missions

| | | |
|---|---|---|
| MetOp | ongoing | GOME-2, IASI |
| NPP / NPOESS | 2010/13 | OMPS, CRIS |
| MTG-S | 2018 | IRS |
| post-EPS | 2018/20 | IRS |
| Asia ? | | |

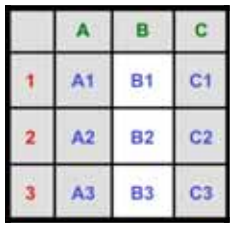
- stratospheric ozone monitoring well covered
- some contribution to NWP
- some contributions to tropospheric applications

Main deficiencies:

- ➢ horizontal resolution in UV-VIS-NIR
- ➢ temporal resolution

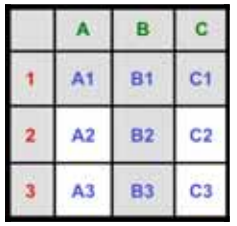
## Main gaps in current / planned operational system

- High temporal and spatial resolution space-based measurements of tropospheric (PBL) composition for application to air quality




- Climate gases ($CO_2$, $CH_4$ and precursor CO) and aerosol monitoring with sensitivity to the PBL


- High vertical resolution measurements in the UT/LS region for ozone and climate applications



## Mission concept for ozone and climate applications in the UTLS

**Instrumentation options:**
either mm-wave or mid-IR limb-sounder

**System:** sun-synchronous LEO platform

***Maturation of operational application to be pursued.***
***Choice of instrument type open.***
***Mission to be considered after clarification of these points.***

# System trade-off for climate protocol monitoring and air quality

**1. Air quality and climate protocol monitoring missions can be combined due to large overlap of requirements ($CO_2$ excluded).**

**2. System concept driven by air quality geographical coverage and time resolution requirements.Trade-off between geographical coverage and temporal sampling:**

| Option | Latitude range [deg] | Longitude range [deg] | Revisit time | Implementation option |
|---|---|---|---|---|
| 1 a | 30 - 65 N | 30 W - 45 E @ 40 N | 0.5 - 1 h solar ch.<br>0.5 - 2 h thermal ch. | 1 GEO |
| 1 b | All | All | 24 h @ fixed L.T. | 1 SSO |
| 2 | 30 - 60 N &<br>30 - 60 S | All | 2 h | Constellation of drifting LEO |
| | 30 N - 30 S | All | 6 h | |
| 3 | All | All | 4 h | Constellation of SSO |

## Option 1: 1 GEO + 1 LEO in sun-synchronous orbit

➢ **cost prohibitive for stand-alone realisation →**
**only possible as additional payloads on MTG and post-EPS**

\+ ***high temporal and spatial sampling over Europe and around***
\+ ***least variation in observation geometries* → facilitates data usage**

\- ***no redundancy: two MTG-Sounder platforms for 15 years***
\- ***incompliant with GEO thermal IR requirements ($O_3$, CO profiles)***
\- ***no PBL-sensitive CO measurement at high temporal resolution***
\- ***no multi-directional polarisation imaging***
\- ***pointing and co-registration difficult***

***focus on European air quality, also stratospheric ozone monitoring***

## Option 2: Constellation of 3-4 LEO satellites in drifting orbit

\+ *high temporal sampling over most of the polluted areas globally*

\+ *favourable redundancy concept (all satellites identical)*

\- *misses polar ozone*

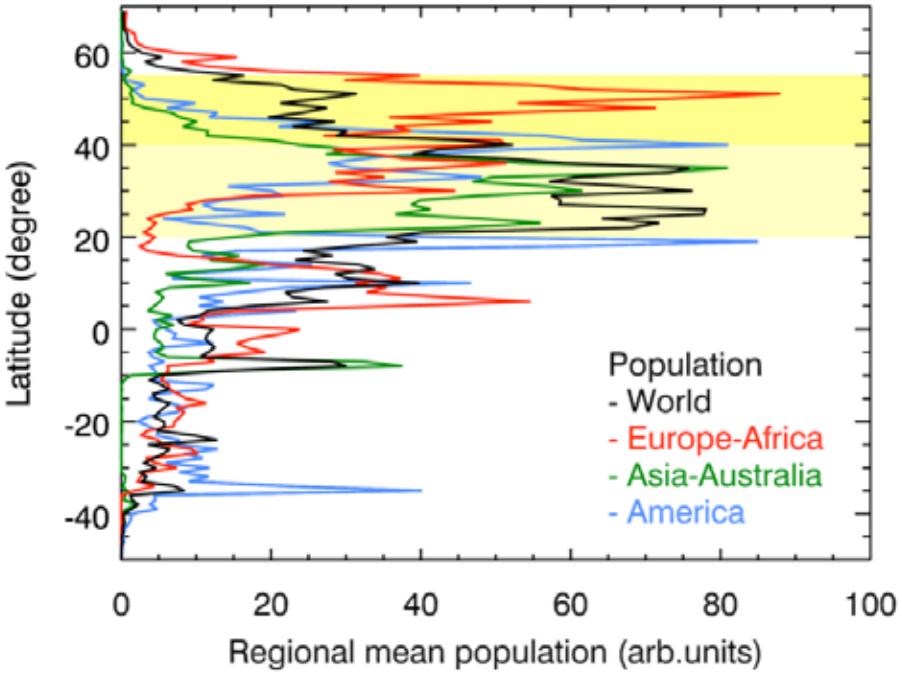
→ *relying on NPOESS or futu*

\- *misses $CH_4$ from melting pern*

→ *relying on NPOESS / post-*

\- *impact of non-sunsynch orbit*

**Higher orbits (~1000km) would improv**
**prohibited by radiation environment ar**




*focus on quasi-global air quality – high population density*

**Courtesy:**
**P. Veefkind**

## Option 3: Constellation of 3 LEO satellites in sun-synch orbit

+ *full global coverage*
+ *maturity*
+ *highest synergy with meteorological measurements*

- *temporal resolution less favourable for air quality (however improving with increasing latitude)*

*Climate, air quality and stratospheric ozone monitoring*

## Selection of system concept

**Option 1 has been selected**

- lowest cost
- synergy with meteorological payload through implementation on Eumetsat platforms
- highest diurnal sampling frequency over Europe

**Mission concept for climate protocol monitoring (lower troposphere) and air quality applications**

**Instrumentation:**

- UV-VIS-NIR-SWIR spectrometer for $O_3$, $NO_2$, $SO_2$, $H_2CO$, $CH_4$, CO, aerosol
- thermal IR sounder for $O_3$, CO and $CH_4$ profiles and $HNO_3$ + others
- cloud imager

**System:** 1 GEO platform (Europe) and 1 sun-synchronous LEO platform.

## Implementation of S4&5 on Eumetsat platforms

- **Sentinel 4 will be a realised as**
  - addition of a UVN spectrometer on the MTG-S platforms;
  - utilisation of TIR data from the IR sounder onboard the same platforms; and
  - utilisation of imager data from the MTG-I platforms.
- **Sentinel 5 will consist of**
  - a UVNS spectrometer embarked on the post-EPS platforms;
  - utilisation of the EUMETSAT post-EPS IR sounder which addresses requirements for both meteorology and atmospheric chemistry (the latter consistent with the Sentinel 5 IR sounding requirements);
  - utilisation of post-EPS imager data;
  - utilisation of multi-directional polarisation imager if implemented.

## The need for a Sentinel 5 precursor (1/2)

### *1. Continuity of data*

Research missions (here Sciamachy, OMI, TES, Mopitt) stop ≤ 2014.

post-EPS launches ~2020.

Metop (even more NPOESS) data do not satisfy S5 requirements:

- CO and $CH_4$:
  - No measurement by GOME-2;
  - IASI data have little PBL sensitivity.
- Spatial resolution of GOME-2 is 40 x 80 $km^2$,
  OMI: 13 x 24 $km^2$, S5 requirement: 10 x 10 $km^2$.

## The need for a Sentinel 5 precursor (2/2)

### *2. Transition to operational scheme*

- Afternoon orbit required for AQ forecast (Metop: 9:30h).
- Use synergy S5 precursor – Metop to start into observation of diurnal variation, as needed for AQ monitoring. (Will be picked up by S4 later).
- improved radiometric sensitivity of S5 precursor

## Requirements for Sentinel 5 precursor

Requirements are those of S5, except

- Local time (see above)

  ➡ fly in loose formation with NPOESS C1

  (synergy with imager, OMPS-limb, CRIS)

- Thermal IR part is dropped, considering
  - availability of IASI data,
  - the transitional nature of the precursor mission,
  - programmatic constraints.

## Programmatic status

| | |
|---|---|
| **Sentinel 5 precursor** | approved and funded (NL co-funding)<br>phase A/B1 ITT out soon, launch 2014 |
| **Sentinel 4** | approved and funded by ESA ministerial council<br>phase A running, launch 2018<br>final approval of MTG-S by Eumetsat expected 2010/11 |
| **Sentinel 5** | preparatory activities approved<br>phase A to start 2010, launch $\geq$ 2018<br>final approval and funding expected 2011 (ESA and Eumetsat) |

## Some results of Camelot study (1)

*Camelot consortium: KNMI, RAL, U. Leicester, SRON, FMI, BIRA-IASB, CNR-IFAC, U. Köln, Noveltis*

**Ozone**

- Both UV and TIR have limited sensitivity to PBL
- Combination of a posteriori covariances promises ~30-50% precision in PBL ( := 0-2km layer)
- Averaging kernel for “PBL” extends to ~7km altitude
- Iterative synergistic retrieval remains to be demonstrated
- Observation of diurnal variation in PBL challenging

**$NO_2$**

- Strong benefit from $O_2$-A band in cloudy conditions
- Good correlation OMI / ground-based (where expected)
- Observed diurnal variation convolved with PBL dynamics (Av. Kernel)

## Some results of Camelot study (2)

### $CH_4$

- Direct retrieval: high sensitivity to cloud and aerosol
- Calibration of AMF using $CO_2$ (1.6 μm band): sensitivity to assumed $CO_2$ abundance
- Combination of 1.6 and 2.3 μm bands required (implementation on Sentinel 5)

### Aerosol

- Proper characterisation of aerosol requires multi-spectral, multi-directional, multi-polarisation imager (3MI)
- UV and SWIR channels desirable in 3MI

## Some results of Camelot study (3)

### Thermal IR

- Drastic change of requirements following IASI success:
  From 2-3 narrow bands ($O_3$, CO [,$HNO_3$]) to wide-band instrument
- Target species: $O_3$, CO, $HNO_3$, $CH_4$, $H_2O$, $NH_3$, $CH_3OH$, PAN, volcanic $SO_4$, $C_2H_4$, $C_2H_2$, HCN, CFC-11, CFC-12
- spectral resolution 0.075 – 0.3 $cm^{-1}$ unapodised
- Implementation in combined meteo – chem instrument on post-EPS

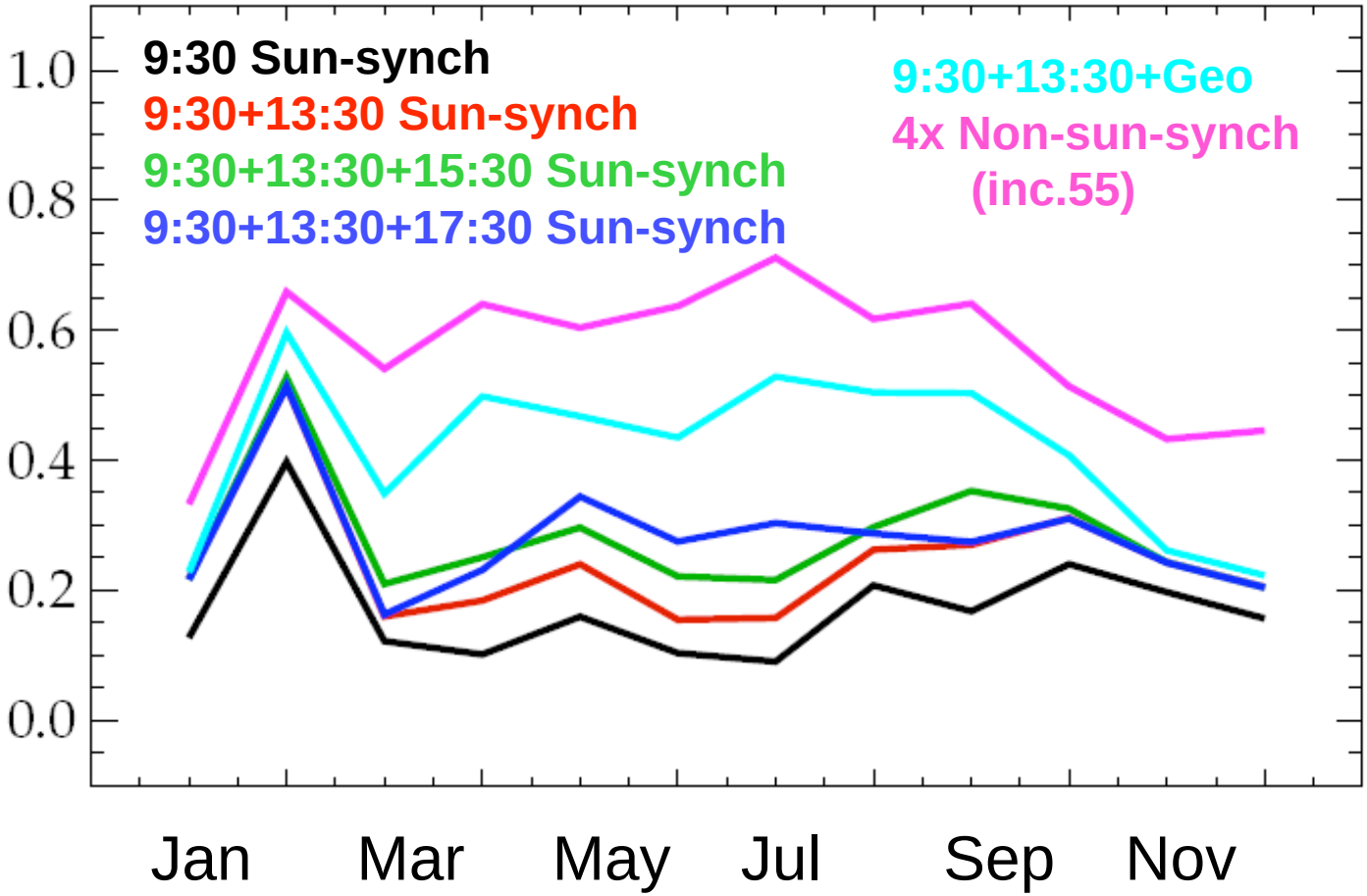
## Some results of Camelot study (4)

### Sampling statistics for orbit configurations

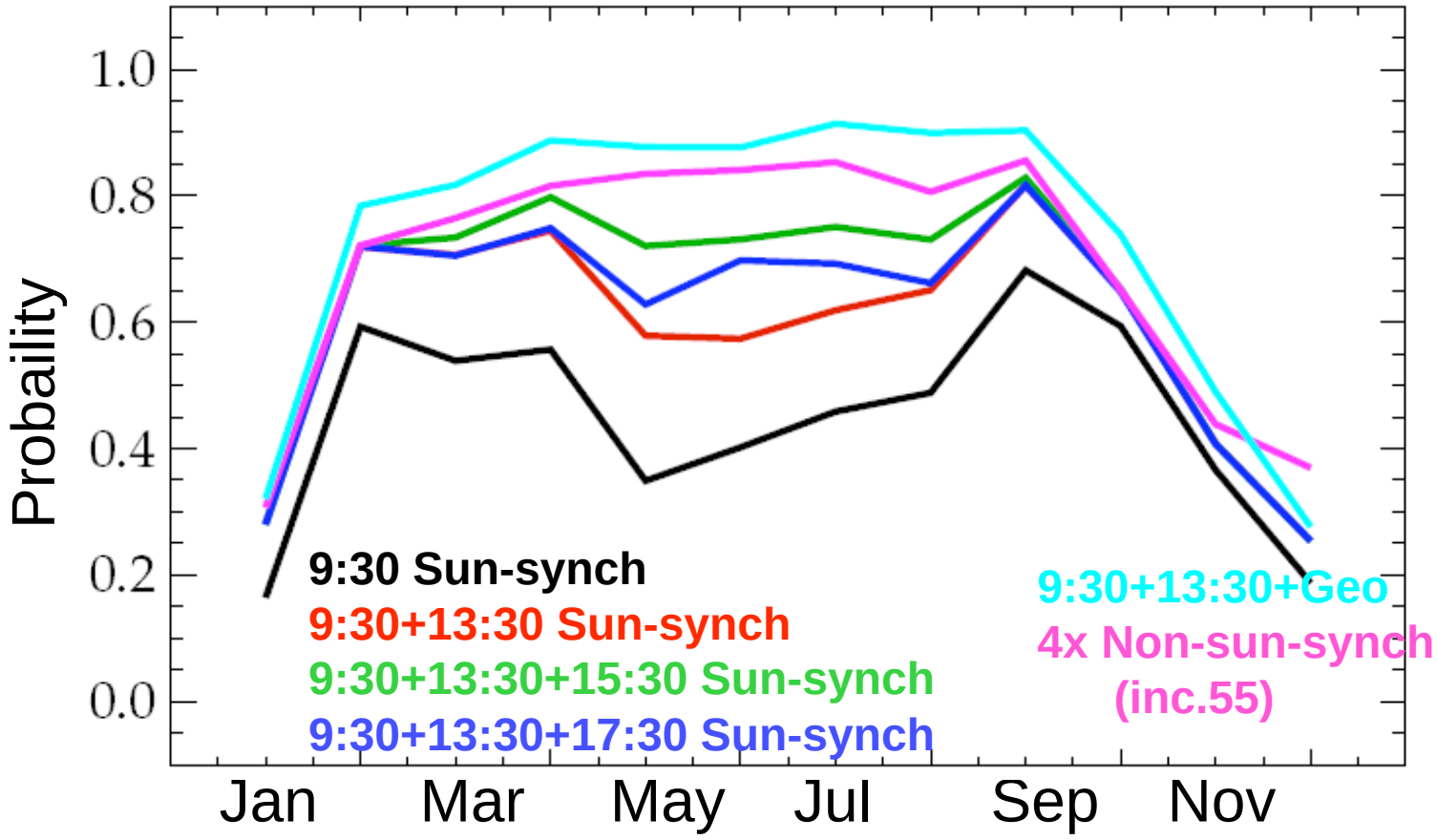
- based on SEVIRI cloud statistics
- taking account of retrieval sensitivity to cloud statistics and observation geometry
- Comparing retrieval accuracies to requirements
- Results shown are observation probabilities per 24h for
  - Tropospheric ozone column from UV
  - London (51°N)
  - 10km pixel size (GEO), 10km sub-satellite pixel size (LEO)
  - 30km field of regard

  and should be seen as examples.

## Probability of at least 1 cloud free observation

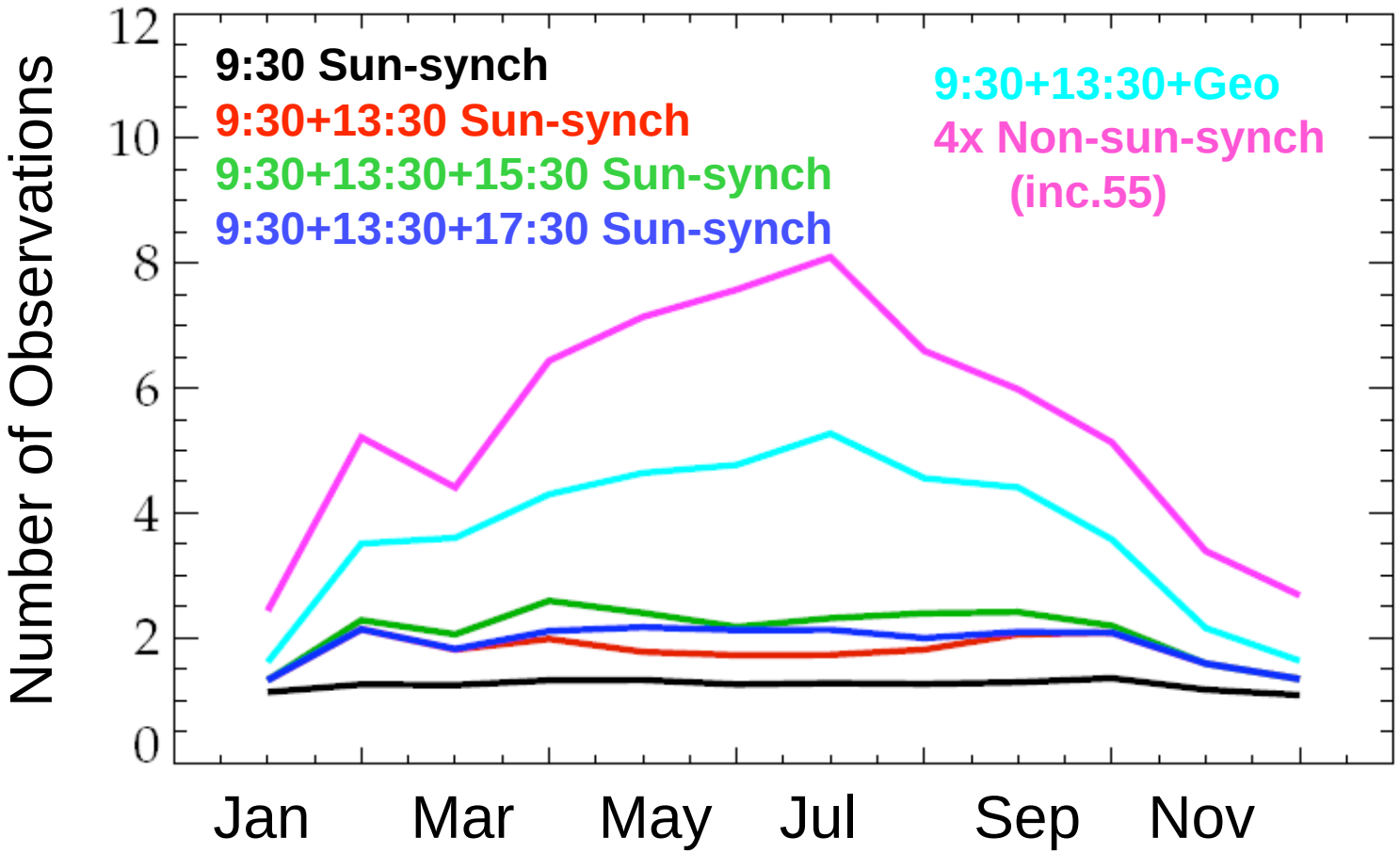


## Probability of at least 1 observation meeting user requirement (20%)



**Number of hours with observation meeting requirement during day,**

- **If at least one cloud free observation obtained during the day**



**Thank you!**

## $CO_2$

$CO_2$ Kyoto protocol mission out of reach (confirmed by dedicated ESA study)

- Random and systematic measurement error requirements
- Uncertainties of inverse modelling (transport PBL – free troposphere)
- Uncertainties in modelling of natural surface fluxes

$CO_2$ mission on total surface fluxes, concentration monitoring or NWP

- First significant results from AIRS and Sciamachy available
- Dedicated research mission (GOSAT) recently launched, OCO failed.
- Very demanding spec's → a mission of its own

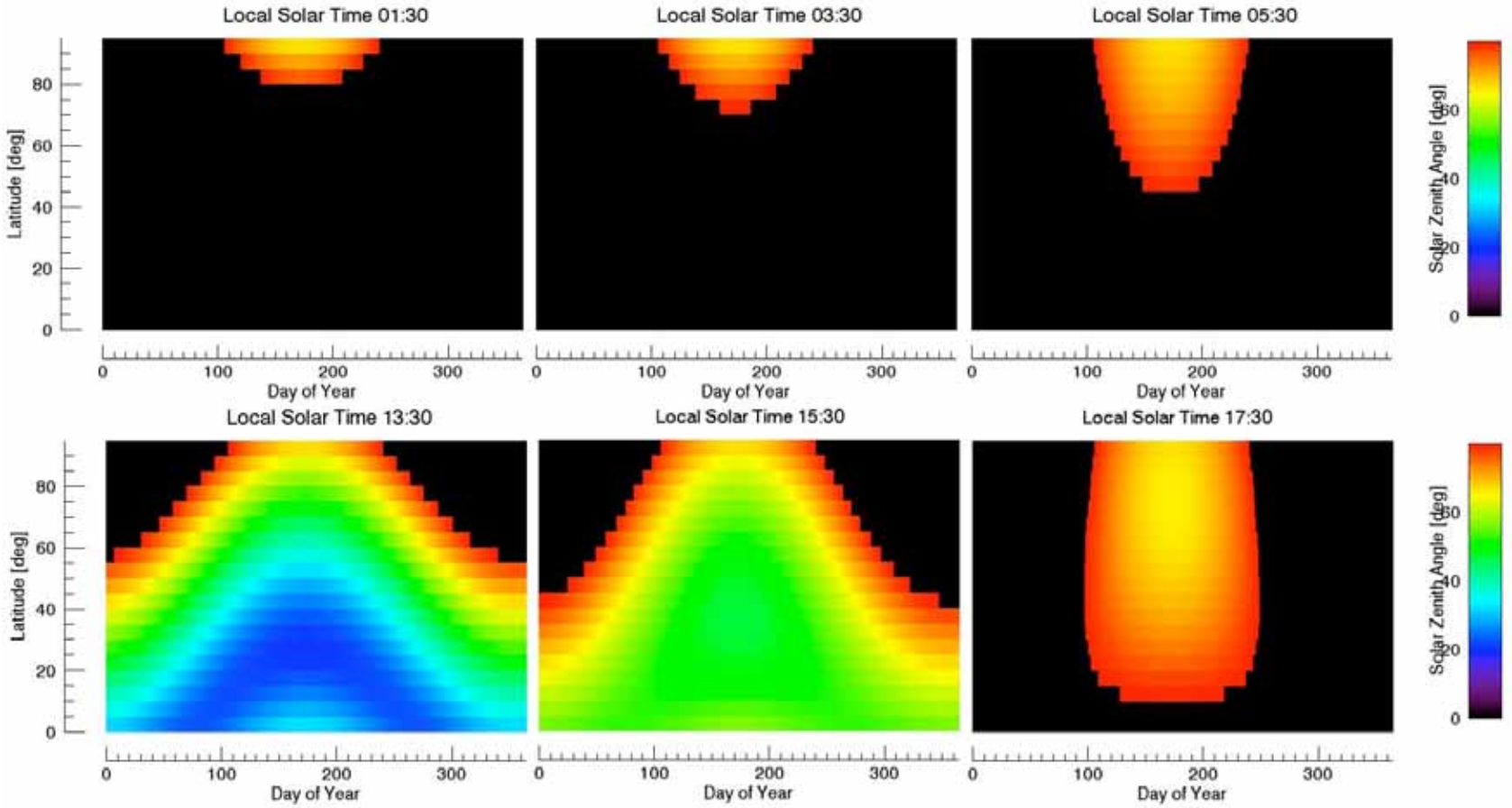
→ **$CO_2$ considered immature for operational mission.**

**Situation may be revisited when GOSAT results available.**

## Local time of Sentinel 5 precursor orbit

**MRD** follows advice from Camelot study:

- ***early*** afternoon orbit most suitable for continuation of the long term record of short-lived tropospheric species, which has been started in 2004 with OMI at a local time of 13:45h;
- synergistic exploitation of simultaneous measurements form NPOESS 13:30h platform possible: CRIS IR data and stratospheric ozone profiles by OMPS-limb, as well as cloud data from imager;
- early afternoon provides better observation conditions in solar channels than late afternoon, due to more favourable solar zenith angles (see next slide).




useful data in solar range for SZA < 80° (ref. TRAQ, Camelot)

➡ late afternoon (17.30h) implies summer only mission of UVNS