

Committee on Earth Observation Satellites (CEOS)

CEOS Air Quality Gap Analyses

Brian Killough, CEOS SEO

CEOS ACC-4 Workshop

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Why a Gap Analysis ?

- We need to answer the following questions ...

What are the high priority air quality measurements missing from current mission plans and what missions are needed to meet future requirements ?

Are there specific recommendation that can be made to the CEOS space agencies to address air quality in the future ?

- Gaps are defined as either a missing measurement in time (science or operational) or the inability to meet a requirement (atmospheric region, resolution, revisit rate, algorithms, technologies).
- The result of the ACC-3 Workshop was a report including specific recommendations to space agencies. ACC-4 may desire to produce a similar report or addendum focused on Air Quality.



Requirements Summary

- Requirements exist in many places for space-based measurements of air quality. These include: IGACO, GCOS, NASA Decadal Survey and Science Plan, ESA CAPACITY, GMES, MTG and Post-EPS. This analysis focused on measurements of: **O₃, CO, NO₂, SO₂, Aerosols (PM)**
- The ACC sponsored a “gap analysis” in 2008 to gather requirements, gather the current and planned set of missions, and determine current or future “gaps”. The analysis was conducted by Rutherford Appleton Laboratories (RAL) and funded by the CEOS Systems Engineering Office (SEO). The final report is available at the CEOS website (www.ceos.org, see Constellations-ACC and Documents).
- The **revisit time** requirements for Air Quality Forecasting (**GMES 4hrs** – H₂O, O₃, HNO₃, CO, NO₂, CH₂O, N₂O₅, SO₂, Aerosols) and Health or Chemical Weather Forecasting (**NASA 1hr**, O₃, CO, NO₂, CH₂O) are the driving requirements. **A constellation of satellites OR several GEO satellites are required to meet these revisit rate requirements.**



Air Quality Requirements and Gap Summary

Parameter	Key Requirements	Primary Measurement Approach	Gap Summary
O ₃	Health , Regional and Global, 48hrs, 10km Horiz, PBL Chem Weather , Regional, 1hr, 5km Horiz, Trop Column AQ Forecast , Reg and Global, 4hrs, 5km Vert, Trop	Nadir UVN , Lidar	Good Nadir UVN , Limited Limb and Occultation (high res vertical) GMES 4hr revisit unmet
Aerosols	Health , Regional and Global, 4hrs, 10km Horiz, Total Column Chem Weather , Regional and Global, FT Aerosol Column , 2km Vert, Trop Column Aerosol Type+OD , Regional and Global, 4hrs, Trop	Multiple Instruments (Nadir, Limb, Occult)	Broad requirements met by many Nadir instruments. Limited lidar, limb and polarimeter measurements. GMES and Health 4hr revisit unmet for forecasting
CO	Health , Regional and Global, 1hr, 1km Vert, PBL Chem Weather , Regional, 1hr, 5km Vert/Horiz, FT AQ Forecast , Reg and Global, 4hrs, 5km Vert, Trop	Nadir UVN , Nadir IR , Limb MW	Good Nadir IR and UVN , Partial Limb MW , GMES 4hr revisit unmet, Health/Chem Weather 1hr revisit unmet
NO ₂	Health , Regional and Global, 1hr, 1km Vert, PBL Chem Weather , Regional, 1hr, 5km Horiz, Trop Column AQ Forecast , Reg and Global, 4hrs, 20km Horiz, Trop	Nadir UVN , Limb IR	Good Nadir UVN , Partial Limb IR , GMES 4hr revisit unmet, Health/Chem Weather 1hr revisit unmet
SO ₂	Health , Regional and Global, 1hr, 1km Vert, PBL Chem Weather , Regional, 1hr, 5km Horiz, FT AQ Forecast , Reg and Global, 4hrs, 20km Horiz, Trop	Nadir UVN	Good Nadir UVN , GMES 4hr revisit unmet, Health/Chem Weather 1hr revisit unmet

More detail on requirements, measurements and gaps are found in the RAL report.



Ozone Summary

High Resolution Ozone Vertical Profiles (Limb and Occultation)

Mission	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Odin																								
ENVISAT																								
SCISAT																								
Aura																								
NPP																								
ALTIUS																								
PREMIER																								
Sentinel-5 Post-EPS																								
GACM-1																								

Summary

- **34 Missions** (including 3 Geosynchronous) are planned from 2009 to 2027 to measure total column ozone. There are no gaps in total ozone column measurements due to a large number of operational missions (NOAA, China, and EUMETSAT) though consistency among data sets is still a challenge.
- Few missions are planned for high vertical resolution ozone measurements (via limb or occultation) beyond 2013. Limited redundancy exists due to instrument differences and measured constituents. This gap limits continued evaluation of ozone recovery (Montreal Protocol).
- Uncertainty exists with future missions since **ALTIUS** is a proposed concept from Belgium, **PREMIER** is in competition with other missions, limb profiling on **Sentinel-5 Post-EPS** is uncertain, and **GACM-1** may be delayed beyond 2030 due to limited NASA funding for DS missions.

GEO mission contributions shown on a separate chart.



Aerosol Summary

Lidar Instruments

Mission	Instrument	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
ICESat	GLAS																										
Calipso	CALIOP																										
ADM-Aeolus	ALADIN																										
Earth-CARE	ATLID																										
ICESat-II	GLAS																										
ACE	Lidar																										

Limb Spectrometers

Mission	Instrument	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
Envisat	GOMOS,MIPAS																										
Aura	HIRDLS																										
ISTAG	MAVELI																										

Polarimeters

Mission	Instrument	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
PARASOL	Polder																										
Glory	APS																										
ISTAG	MAPI																										
NPOESS-1	APS																										
ACE	APS																										

Summary

- **35 Nadir Imagers** are planned from 2009 to 2027 (i.e., AVHRR, MODIS, VIIRS). These missions will adequately measure Aerosol Optical Depth (total column) for extinction and Aerosol Effective Radius (profiles) for micro-physical properties (size and shape).
- **15 Nadir Spectrometers** are planned from 2009 to 2027 (i.e., GOME, SCHIAMACHY, CrIS, TANSO-FTS). These missions will adequately measure Aerosol Absorption Optical Depth (column) to infer aerosol type and optical absorbing properties.
- A limited number of **Lidars** and **Limb Spectrometers** are planned for vertically resolved extinction and backscatter and a limited number of **Polarimeters** are planned for Aerosol Optical Depth and optical absorbing properties.



Ozone Precursor - CO

Mission	Instrument(s)	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
Odin	OSIRIS, SMR																										
ERS-2	GOME-1																										
NOAA-16	SBUV-2																										
ENVISAT	SCIAMACHY																										
NOAA-17	SBUV-2																										
Terra	MOPITT																										
Aqua	AIRS																										
Aura	TES, OMI, MLS																										
NOAA-18	SBUV-2																										
Metop-A	IASI, GOME-2																										
FY-3A	TOU-SBUS																										
GOSAT	TANSO-FTS																										
FY-3B	TOU-SBUS																										
FY-3C	TOU-SBUS																										
NOAA-19	SBUV-2																										
NPP	OMPS, VIIRS																										
FY-3D	TOU-SBUS																										
Metop-B	IASI, GOME-2																										
FY-3E	TOU-SBUS																										
FY-3F	TOU-SBUS																										
NPOESS-C1	OMPS, VIIRS																										
GCOM-C	SGLI																										
Sentinel-5 Precursor	UVN Spec																										
Metop-C	IASI, GOME-2																										
PREMIER	STEAM-R																										
FY-3G	TOU-SBUS																										
NPOESS-C2	VIIRS																										
Sentinel-4 (GEO)	UVN Spec, IR Spec																										
NPOESS-C3	VIIRS																										
Sentinel-5 Post-EPS	UVN Spec																										
NPOESS-C4	VIIRS																										
GEO-CAPE	UVN Spec, IR Spec																										
ACE	UVN Spec																										
GACM-1	UVN Spec, IR Spec, MW Spec																										

Current baseline
Current extended
Future Planned

Summary

- Significant contributions to CO measurements from **Nadir UVN and IR** instruments. Some contributions from **MW limb**.
- Adequate near-term missions through ~2010. Long-term plans depend primarily on NOAA operational missions (OMPS and VIIRS instruments), China operational missions (TOU-SBUS instrument), ESA Sentinels (UVN Spectrometer instrument) and EUMETSAT Metop missions (GOME-2 and IASI instruments).
- NASA Decadal Survey missions add contributions beyond 2020 due to funding constraints.



Ozone Precursors - NO₂

Mission	Instrument(s)	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
Odin	OSIRIS																										
ERS-2	GOME-1																										
NOAA-16	SBUV-2																										
ENVISAT	SCIAMACHY, MIPAS																										
NOAA-17	SBUV-2																										
Aura	OMI, HIRDLS																										
NOAA-18	SBUV-2																										
Metop-A	GOME-2																										
FY-3A	TOU-SBUS																										
FY-3B	TOU-SBUS																										
FY-3C	TOU-SBUS																										
NOAA-19	SBUV-2																										
NPP	OMPS																										
FY-3D	TOU-SBUS																										
Metop-B	GOME-2																										
FY-3E	TOU-SBUS																										
FY-3F	TOU-SBUS																										
NPOESS-C1	OMPS																										
GCOM-C	SGLI																										
Sentinel-5 Precursor	UVN Spec																										
Metop-C	GOME-2																										
PREMIER	IMIPAS																										
FY-3G	TOU-SBUS																										
Sentinel-4 (GEO)	UVN Spec																										
Sentinel-5 Post-EPS	UVN Spec, IR limb																										
GEO-CAPE	UVN Spec																										
ACE	UVN Spec																										
GACM-1	UVN Spec																										

Current baseline
Current extended
Future Planned

Summary

- Significant contributions to NO₂ measurements from **Nadir UVN** instruments. Some contribution from **Limb IR**.
- Adequate near-term missions through ~2011. Long-term plans depend primarily on China operational missions (TOU-SBUS instrument), ESA Sentinels (UVN Spectrometer instrument) and EUMETSAT Metop missions (GOME-2 instrument).
- Partial contributions from limb IR instruments exists for ENVISAT (MIPAS), Aura (HIRDLS), PREMIER (IMIPAS) and Sentinel-5 Post-EPS (IR Limb Spectrometer). Future missions are uncertain and not operational.
- NASA Decadal Survey missions add contributions beyond 2020 due to funding constraints.



Ozone Precursors - SO₂

Mission	Instrument(s)	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
Odin	OSIRIS																										
ERS-2	GOME-1																										
NOAA-16	SBUV-2																										
ENVISAT	SCIAMACHY																										
NOAA-17	SBUV-2																										
Aura	OMI																										
NOAA-18	SBUV-2																										
Metop-A	GOME-2																										
FY-3A	TOU-SBUS																										
FY-3B	TOU-SBUS																										
FY-3C	TOU-SBUS																										
NOAA-19	SBUV-2																										
NPP	OMPS																										
FY-3D	TOU-SBUS																										
Metop-B	GOME-2																										
FY-3E	TOU-SBUS																										
FY-3F	TOU-SBUS																										
NPOESS-C1	OMPS																										
GCOM-C	SGLI																										
Sentinel-5 Precursor	UVN Spec																										
Metop-C	GOME-2																										
FY-3G	TOU-SBUS																										
Sentinel-4 (GEO)	UVN Spec																										
Sentinel-5 Post-EPS	UVN Spec																										
GEO-CAPE	UVN Spec																										
ACE	UVN Spec																										
GACM-1	UVN Spec																										

Current baseline
Current extended
Future Planned

Summary

- Significant contributions to SO₂ measurements from **Nadir UVN** instruments.
- Adequate near-term missions through ~2011. Long-term plans depend primarily on China operational missions (TOU-SBUS instrument), ESA Sentinels (UVN Spectrometer instrument) and EUMETSAT Metop missions (GOME-2 instrument).
- NASA Decadal Survey missions add contributions beyond 2020 due to funding constraints.



GEO Mission Contributions

Mission	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
China FY-4 O/A																	
GOES-S																	
GOES-R																	
China FY-4 O/B																	
China FY-4 O/C																	
MP-GEO																	
Sentinel-4																	
China FY-4 O/D																	
China FY-4 O/E																	
GEO-CAPE																	

Summary

- **GEO Missions** are planned from 2012 to 2025 by NASA, NOAA, ESA, KARI and China. There are **NO current GEO missions** for atmospheric composition. Due to differences in their orbit location and measurements capabilities, these missions should **NOT** be considered redundant and make very different contributions to global atmospheric composition measurements.
- **China's FY-4** missions are located over the eastern hemisphere (105-deg east) and utilize an experimental instrument and may measure column NO₂. **NOAA's GOES** missions are located over the western hemisphere (135-deg west) and are focused primarily on operational meteorology with measurements of aerosol total column but no measurements of gases. **NASA's GEO-CAPE** mission will be located over the eastern U.S. (80-deg west) and focused on air pollution forecasting and transport using measurements of aerosols, O₃, CO, HCHO, SO₂ and NO₂. **ESA's Sentinel-4** mission will be located over Europe (~0-deg) and will have similar capabilities to GEO-CAPE. **KARI's MP-GEO** mission will be located over Asia (~120-deg east).
- GEO missions are the **best approach** to meet regional revisit time requirements for Air Quality Forecasting (GMES, 4-hours) and Health or Chemical Weather Forecasting (NASA, 1-hour)

- **Ozone** - Adequate nadir instruments exist for ozone and aerosols, though consistency among data sets is still a challenge. Vertical profiles (via limb or occultation) for ozone are limited due to instrument variations and uncertainty in long-term plans.
- **Aerosols** - Adequate nadir instruments exist for aerosol optical depth and micro-physical properties. A limited number of lidars, limb spectrometers and polarimeters will measure vertically resolved extinction, backscatter and optical properties.
- **CO, NO₂ and SO₂** - Nadir instruments provide adequate data through 2011. Limited long-term missions will place an emphasis on data sharing and data consistency from operational missions (NOAA, ESA, EUMETSAT, China). Vertical information for NO₂ is limited due to a lack of Limb measurements.
- **GEO missions** - variations in orbits and measurements limit constant global coverage. Overall, GEO missions are the best approach to meet regional revisit time requirements for Air Quality Forecasting (GMES, 4-hours) and Health or Chemical Weather Forecasting (NASA, 1-hour). There is a good opportunity for coordination among the GEO missions (data sharing, cal-val, algorithms).



Proposed Next Steps

- Develop an ACC-4 Report and a set of recommendations for Air Quality in time for the SIT-24 Meeting in Darmstadt, Germany (September 2009).
- Recommend a CEOS multi-agency GEO/LEO constellation concept with adequate spatial and temporal sampling to achieve forecasting requirements (1 to 4 hours revisit).
- Recommend the development of more instruments or new technologies critical to addressing the needs of space-based air quality requirements in the future.
- Recommend coordination among planned GEO missions. This includes, but is not limited to, data sharing, algorithm development, and cal-val.

BACKUP



ACC Mission Summary

Current Missions

Mission Name	Agency	Instruments	Launch
ERS-2	ESA	GOME-1, ATSR-2	1995
NOAA-15 (NOAA-K)	NOAA	AVHRR-3, HIRS-3	1998
OceanSat1	ISRO	OCM	1999
Terra	NASA	MOPITT, MODIS	2000
Odin	CNES	SMR, OSIRIS	2001
NOAA-16 (NOAA-L)	NOAA	AVHRR-3, SBUV-2, HIRS-3	2001
ENVISAT	ESA	SCIAMACHY, MIPAS, AATSR, GOMOS, MERIS	2002
MSG-1 (Meteosat-8)	EUMETSAT	SEVIRI	2002
Aqua	NASA	AIRS, MODIS	2002
NOAA-17 (NOAA-M)	NOAA	AVHRR-3, SBUV-2, HIRS-3	2002
SCISAT	CSA	ACE, MAESTRO	2003
ICESAT-1	NASA	GLAS	2003
PARASOL	CNES	Polder	2004
Aura	NASA	MLS, OMI, TES, HIRDLS	2004
NOAA-18 (NOAA-N)	NOAA	AVHRR-3, SBUV-2, HIRS-4	2005
MSG-2 (Meteosat-9)	EUMETSAT	SEVIRI	2005
CALIPSO	NASA	CALIOP-Lidar	2006
Metop-A (Metop-1)	EUMETSAT	GOME-2, IASI, AVHRR-3	2006
FY-3A	CMA	VIRR, IRAS, TOU/SBUS	2008
Meteor-M N1	Russia	MSU-MR	2008
GoSAT	JAXA	TANSO-FTS, TANSO-CAI	2009
NOAA-19 (NOAA-N')	NOAA	AVHRR-3, SBUV-2, HIRS-4	2009

Planned Missions

Mission Name	Agency	Instruments	Launch
FY-3B	CMA	VIRR, IRAS, TOU/SBUS	2009
FY-3C	CMA	VIRR, IRAS, TOU/SBUS	2009
GLORY	NASA	APS	2009
Meteor-M N2	Russia	MSU-MR	2009
ADM-Aeolus	ESA	ALADIN	2010
NPP / NPOESS	NASA	OMPS, VIIRS, CrIS	2010
FY-3D	CMA	VIRR, IRAS, TOU/SBUS	2010
Metop-B (Metop-2)	EUMETSAT	GOME-2, IASI, AVHRR-3	2011
MSG-3 (Meteosat-10)	EUMETSAT	SEVIRI	2011
ISTAG	MAPI	ISRO	2011
Sentinel-3	ESA	OCLI	2012
FY-3E	CMA	VIRR, IRAS, TOU/SBUS	2012
FY-3F	CMA	VIRR, IRAS, TOU/SBUS	2012
FY-4 O/A	CMA	MCSI, LM	2012
ALTIUS	Belgium	Nadir and Limb Sensors	2013
EarthCARE	ESA-JAXA	ATLID, MSI	2013
MSG-4 (Meteosat-11)	EUMETSAT	SEVIRI	2013
GCOM-C	JAXA	SGLI	2013
ASCENDS	NASA	Lidar	2013
NPOESS-C1	NOAA	OMPS (no limb), VIIRS, APS, CrIS	2013
Sentinel-5 (Precursor)	ESA	UVN Spec	2014
GOES-S	NOAA	ABI	2014
GOES-R	NOAA	ABI	2015
PREMIER	ESA-SSC	IMIPAS, STEAM-R	2015
Metop-C (Metop-3)	EUMETSAT	GOME-2, IASI, AVHRR-3	2015
FY-4 O/B	CMA	MCSI, LM	2015
FY-4 O/C	CMA	MCSI, LM	2015
ICESAT-2	NASA	GLAS	2015
FY-3G	CMA	VIRR, IRAS, TOU/SBUS	2016
NPOESS-C2	NOAA	VIIRS, CrIS	2016
Sentinel-4	ESA	IR Spec, UVN Spec	2017
NPOESS-C3	NOAA	VIIRS (no OMPS currently), CrIS	2018
FY-4 O/D	CMA	MCSI, LM	2019
FY-4 O/E	CMA	MCSI, LM	2019
NPOESS-C4	NOAA	VIIRS, CrIS	2020
Sentinel-5 (Post-EPS)	ESA	Nadir UV-Vis Spec, Nadir IR Sounder, Limb IR	2020
GEO-CAPE	NASA	UVN Spec, IR Spec	2020
ACE	NASA	Lidar, Polarimeter, UVN Spec	2020
GACM-1	NASA	UVN, IR, MW Limb Spectrometers	2030



ACC Societal Benefit Mapping

		Societal Benefit Area (SBA)				
		Disaster	Climate	Health	Energy	Ecosystem
ACC Theme	Air Quality	Pollution Events Smoke and Ash from Fires Volcanic Eruptions		Tropospheric Ozone Particulates Sulfur Dioxide (SO ₂)	Chemical (AQ) Forecasting	
	Stratospheric Ozone Shield			Ozone impact to surface radiation	Energy (UV) Forecasting	
	Chemistry and Climate Coupling		GHG impact to radiation Aerosol impact to radiation OH impact to climate			Carbon and Nitrogen Fluxes and Exchange



ACC Measurement Mapping

		Science Topics	Aerosols	Trop Ozone	Strat Ozone	CO2	GHG	NOx
Societal Benefit Area (SBA)	Disaster	Pollution Events Smoke and Ash from Fires Volcanic Eruptions	Aerosols					
	Climate	GHG impact to radiation Aerosol impact to radiation Carbon Fluxes and Exchange	Aerosols			CO2	GHG	
	Health	Tropospheric Ozone Aerosols Sulfur Dioxide (SO2)	Aerosols	Trop Ozone	Strat Ozone			NOx
	Energy	Chemical Forecasting Energy Forecasting	Aerosols		Strat Ozone			
	Ecosystem	Carbon and Nitrogen Fluxes and Exchange				CO2		NOx
		Parameter Summary	Aerosols	Trop Ozone	Strat Ozone	CO2	GHG	NOx
ACC Theme	Air Quality and Climate Forecasting	Pollution (aerosols) Smoke and Ash (aerosols) Volcanos (aerosols) Tropospheric Ozone (O3) Sulfur Dioxide (SO2) Others (CO, NOx)	Aerosols	Trop Ozone				NOx
	Ozone and Surface UV	Ozone - O3 Aerosols Others: NOx, H2O, HNO3, CH4 Halogens+CFC	Aerosols		Strat Ozone		GHG	NOx
	Composition and Climate Interaction	GHG (O3, CO2, CH4) Aerosol properties	Aerosols			CO2	GHG	NOx